Experimental Electricity and Magnetism

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EXPERIMENTAL SCIENCE PART III.

Experimental Electricity and Magnetism

BY

S. E. BROWN, M.A. (Cantab.), B.A., B.Sc. (Lond.)

HEADMASTER OF LIVERPOOL COLLEGIATE SCHOOL, FORMERLY
SENIOR SCIENCE MASTER AT UPPINGHAM

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PREFACE

THIS text-book is an attempt to give the student, from the outset, the benefits derived from the recent advance in our knowledge of the nature of electricity.

It is claimed that, by realizing the properties of Nature's unit—the Electron—the beginner can gain a more vivid conception of electric pressure and electric current than was possible before the electron theory was formulated.

The method of teaching, based on practical experiment, that has proved to be useful throughout the series of manuals known as "Experimental Science," is continued here.

Many young students build up their knowledge of electricity on a foundation of the elementary principles of Measurement, Hydrostatics, Mechanics, Heat and Chemistry, acquired during the first two or three years of a Secondary School course; those who do not possess this ground work, should add to their acquaintance with the concept of Energy, while reading the earlier chapters of the book.

The Matriculation syllabus is covered fully by this volume. Practical work is carried to the standard of the Higher School Certificate, so that preparation for the second examination may be completed with only the aid of a few notes from the teacher in order to elaborate the theory of the Experiments.

The chapter on the "Generation and Practical Applications of Electricity," and the detailed description of apparatus, should appeal to Technical School students' and works' apprentices.

It is hoped that the last chapter will convey, to the enthusiast in "Wireless," the essentials of the subject, although necessarily in a condensed form.

As in other books of the series, a special feature has be made of the large number of exercises appended to ea chapter in addition to the worked examples in the text.

In many school laboratories, the benches are supplied wi current from the mains. This main current should alwa pass through a suitably high resistance. Whenever the ma supply is used, the teacher should caution the pupils nev to touch the apparatus with wet hands, and himself ensu that the connections are correct before the main current switched on.

The writer is indebted to Mr J. M. Moir, M.Sc., of th Physical Department of the Liverpool Collegiate Schoo whom he cordially thanks, for drafting the last three chapter preparing the Examples, and collaboration throughout i contriving experiments and in proof-reading.

He also wishes to thank Mr T. V. T. Baxter, M.A., B.Sc Headmaster of Cotham School, Bristol, Mr A. Swithinbank M.Sc., Headmaster of Walton Technical School, Liverpool Mr H. Jennings, B.Sc., of Liverpool Collegiate School, an Mr F. Fairbrother, M.Sc., Headmaster of Leighton Buzzar School, who have again given valuable help and criticism.

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November 1922.

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EXPERIMENTAL ELECTRICITY AND MAGNETISM

CHAPTER I

ELECTRONS, ELECTRIC CHARGES, ELECTRIC CURRENT

1. Electricity in the service of man is a distinguishing feature of the present age. The transformation of water-power and steam-power into the energy of the electric current, which in turn provides heating, lighting, magnetic and chemical effects, is familiar to everyone. Mountainous districts, such as Wales, Norway and Switzerland, furnish instances of the heavy rainfall being utilized to store potential energy in the water collected in lakes and reservoirs among the hills. Long pipe-lines convey this water to the valleys, where at a lower level the kinetic energy of rushing water is used to rotate water-wheels and turbines, which hand on "power" to the dynamos of the generating stations where a current of electricity is produced. Copper cables carry this electric current throughout whole districts to places where it is required for traction and locomotion (electric trams and railways), for working machines through the agency of electric motors, for welding, heating, lighting and cooking, and for chemical uses such as smelting, electrolysis and electroplating.

The lightning flash is one of the manifestations of electricity in motion with which earliest man must have been familiar. We read that the ancients ascribed the thunderbolt to Jove as his peculiar weapon, but it is only in comparatively recent years that the tiniest electric spark and lightning have been shown to be of the same order.

2. The electron—the unit of negative electricity.

The beginner often asks—what is electricity?—what is the electric current? In order to help us to answer these questions and to visualize what we can never hope to see, we must begin by an enquiry into the nature of matter itself.

In our study of elementary chemistry, we learned that (*a*) matter is made up of small particles called atoms ("indivisibles") and (*b*) all atoms of the same element have equal weights. This theory was formulated by John Dalton in 1804. After the lapse of a century, a series of brilliant researches by British, American, French and German scientists has revealed that atoms are not indivisible as was supposed, but are built up of particles which may prove to be electricity itself. At any rate it is now held that electricity pervades all matter. There are recognized by the chemist approximately one hundred different elements—hydrogen, copper, gold and the rest—any one of which is composed of atoms which in the so-called *neutral* or *unelectrified* state resemble each other identically.

An atom of an element in this unelectrified state may be imagined as made up of *two* kinds of matter each possessing an equal, but opposite, neutralizing charge of electricity:

(*a*) the **nucleus**, which is said to be **positively charged**, and (*b*) one or more **negative units** of electricity, called **electrons.**

The term *positive* electron is sometimes assigned to the nucleus of the atom, the other neutralizing particles being called negative electrons. In thi book however the word electrons indicates the negatively charged particles only

Although, as we have just said, there are nearly one hundred different chemical elements, *i.e.* there are nearly one hundred different kinds of *positive* atomic **nuclei,** yet *there is only one kind of electron. All electrons are identical*[1]; but each atomic nucleus ($+^{ve}$) is capable of attaching to itself a *definite number* of electrons ($-^{ve}$ units of electricity) which render the atom neutral or uncharged. This number is called the **atomic number** of the particular element. Thus a neutral atom possesses (*a*) a positive nucleus together with (*b*) its atomic number of electrons or units of negative electricity, *e.g.*

---

[1] Electrons are exceedingly small; their size relatively to that of the atom to which they are attached may be compared as the volume of an airship is to that of the earth. It has been calculated that

(*a*) the radius of an electron (assumed to be spherical) $< 10^{-13}$ cms.; *i.e.* $< \frac{1}{100,000}$ of the radius of any atom;

(*b*) mass of an electron $= \frac{1}{1850}$ of mass of a hydrogen atom;

(*c*) electric charge $= 1{\cdot}6 \times 10^{-20}$ E.M. unit [see § 46];

(*d*) energy required to liberate the first electron from an atom $= 10^{-11}$ ergs (approx.).

A *neutral atom* = positive nucleus + *atomic number* × electrons (-
of hydrogen = ,, ,, of hydrogen[1] + *one* electron ($-^{ve}$)
or copper = ,, ,, of copper + *twenty-nine* electrons
or gold = ,, ,, of gold + *seventy-nine* electrons

The *atomic numbers* are found by arranging the elements in the order of their atomic weights, thus: hydrogen, 1, helium, 2, lithium, 3, etc.

3. Conductors and non-conductors (insulators).

In § 1 we mentioned copper cables as carriers of electricity: we know that telegraph lines are made of iron or copper, that lightning conductors, telephone and electric bell wires, the "live rail" of the electric railway, and the overhead wire of the electric tramway are of copper, and that the *metallic* parts of a flash lamp or of a magneto convey electricity. On the other hand we have noticed that coverings of silk, cotton, india-rubber, pitched and paraffined fabric, and porcelain are used to prevent the escape of electricity. Hence we may divide substances into two classes:

(1) **conductors** which convey electricity readily and are chiefly metals and alloys of metals;

(2) **non-conductors** or **insulators** (chiefly non-metallic substances) which prevent the passage of electricity.

---

[1] It is possible that the nucleus of the hydrogen atom may prove to be the positive counterpart of the electron (unit of negative electricity): but for the present we may say that the unit of positive electricity is the charge which is equal to that on the hydrogen nucleus and which neutralizes the charge of an electron.

Conductors

arranged in the order of their ability to conduct electricity, *i.e.* in order of their *conductance.*

Metals	
Silver	100
Copper	100
Gold	75
Aluminium	54
Iron	10
Alloys	
German Silver (Cu 60 %, Zn 26 %, Ni 14 %)	7·5
Platinoid (Cu 58, Zn 26, Ni 14, W 2)	5
Eureka (Cu 60, Ni 40)	3

Non-conductors

or **insulators** (Lat. insula = island)

- Glass
- Quartz
- Mica
- Rock
- Porcelain and Stoneware
- Pitch
- Shellac
- Resin
- India-rubber
- Vulcanite
- Paraffin
- Oils
- Silk and Cotton
- Wood
- Celluloid
- Pure Water
- Dry Air

Partial or indifferent **Conductors**

Graphite, Gas Carbon, Carbon Filament

4. Conduction and the Electric Current.

The Electron Theory helps us to picture to ourselves some of the conditions inside a metallic ring or closed wire, *e.g.* of copper. We may imagine that the nucleus of each atom is more or less rigid and fixed, with its 29 satellite electrons neutralizing its positive charge and held in control by forces of attraction between the positive nucleus and the negative units or electrons. Some of the electrons, however, we may imagine to be but loosely attached to the nucleus. A small but definite amount of work[1] liberates the first of these electrons, and by the expenditure of more energy others may be detached and migrate to adjoining atoms whose electrons will now exceed the atomic number (29): these atoms will now be *negatively* charged: on the other hand the atoms that have lost electrons are *positively* charged. Each negatively charged atom will now be ready to part with an electron, which will not necessarily be the same electron that has just entered the atom in question; and, in turn, each positively charged atom, *i.e.* with a defect of electrons, will be ready to receive any electron which is loosely attached to an atom near it or is wandering about unattached. In *metals*, it is supposed that such loosely attached or even wandering electrons exist, so that we may imagine transference of electrons taking place by the casting off and absorption of these wandering or readily detached electrons. This ready transference of electrons is called **conduction.** We may further imagine the introduction of a *force* which can direct the migration in any particular direction, and so produce a stream of electrons round the circuit. Such a force which causes a stream of electrons to move between and through the atoms in a definite direction is called an **Electro-Motive Force,** and the stream is called an **Electric Current.**

---

[1] Conversely, by the Law of Conservation of Energy, the *same amount of work is done by* the electron in returning to its atom.

We must imagine then that these Electrons (the ultimate units of negative electricity) are very much smaller than the atoms and the spaces between the atoms. The *speed* of electrons varies but it is high, being comparable to that of light. These minute particles, moving with great velocities, may be imagined as passing freely through the relatively large atoms and the spaces between them; and we may suppose that, in a metallic ring or circuit, where the atoms readily part with and receive electrons, the stream may be caused to pass in a definite direction somewhat in the same way as water or air may be directed in a tube, or may surge to and fro as the pressure is increased or diminished in various parts of the circuit.

As there are forces acting not only between the nuclei and the electrons, but also between the electrons themselves, it is necessary to assume the existence of an all-pervading medium in which the interacting stresses and strains are communicated. This medium we call the **ether** of space.

Unattached **electrons repel each other** with forces acting radially from their centres (assuming the electrons to be spherical) through the ether which surrounds them along lines which are termed "**Lines of Electric Force.**" We may imagine then, that, owing to this mutual repulsion among the electrons, *electric pressure*, or **potential** as it is called, exists, comparable to *hydrostatic pressure* in a gas. The analogy of small rubber balls packed tightly into a bag or squeezed in a stream against resistance through a tube will help us to understand these repelling forces between electrons. Each ball repels its neighbours and the outer balls tend to burst through the bag or tube.

5. Non-conductors or **insulators.** It is assumed that in non-conducting substances [see Table, § 3] electrons cannot move freely, if at all, from atom to atom. Hence a covering of insulating substance round a wire prevents the escape of electrons somewhat in the same way as the tube mentioned above prevented the escape of the rubber balls squeezed through it.

6. Exp. To show that electrons repel electrons, but attract atoms deprived of electrons.

(i) Brush a piece of warmed dry brown paper with a dry clothes-brush: the paper adheres to a dry wall for some considerable time. On the electron theory outlined above the explanation is as follows: the *work done* in overcoming friction between brush and paper separates some of the electrons from their atoms, and transfers electrons from brush to paper; the paper, previously neutral, is now super-charged with electrons, *i.e.* is *negatively* electrified; the atoms in the brush, on the other hand, have lost electrons, so that the brush is *positively* electrified.

(ii) Suspend a small wire stirrup from the insulating stand shown in Fig. 1 [refer to Table of Insulators, § 3]. Two spills of warm dry paper are briskly brushed with a warmed clothes-brush: one of the spills is then placed in the stirrup: on bringing the second piece of paper near to the suspended spill the latter is repelled, but it is attracted by the brush, or by the hand or any unelectrified (neutral) object.

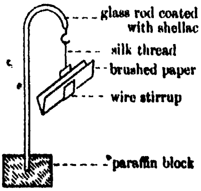


Fig. 1.

(1) **Repulsion** is explained by assuming that both spills are charged with an excess of electrons—"**like charges repel each other.**"

(2) **Attraction** is explained by supposing that the excess of electrons on the paper (the negative charge):

(*a*) attracts the positively charged atoms on the brush;

(*b*) in the case of the hand or any unelectrified object, repels electron from the near atoms to the more remote parts, thus leaving the near part *positively* charged—"**unlike charges attract each other,**" the tw "unlikes" endeavouring to combine and restore the uncharged or neutra condition. In this way the adhering of the brushed paper to the wall i explained.

Exps. (i) **to confirm the above theory;**
(ii) **to illustrate the terms**
(*a*) **induction,**
(*b*) **induced charge.**

Fig. 2 *a*

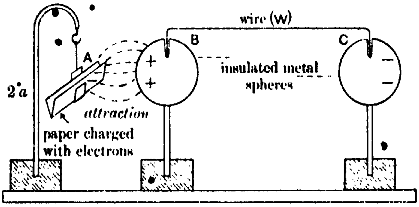
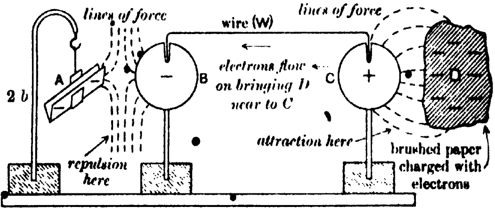


Fig. 2 *b*


lines of force
wire (W)
lines of force
A
−
B
electrons flow on bringing D near to C
C
+
D
repulsion here
attraction here
brushed paper charged with electrons

In Figs. 2 *a*, *b*, *c*, *B* and *C* are two insulated metallic spheres[1] eac having a small hole or metal ring at the top.

W is a wire connecting *B* and *C* which may be lifted off quickly by mean of a shellac-coated glass rod, *R*.

A is the insulated and suspended spill, *negatively*-charged (*i.e.* with electrons in excess).

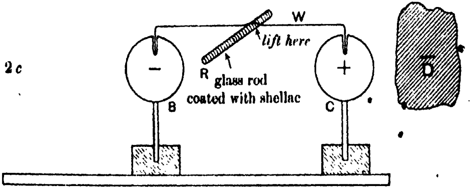
In Fig. 2 *a* the unelectrified but connected spheres are placed so that *B* is brought near to *A*. Attraction is noticed between *A* and *B*, becaus

[1] Wooden balls covered with tin-foil serve the purpose of metal spheres.

electrons in the sphere system *B* and *C* are repelled so that there is an excess of electrons on *C* and a dearth of them on *B*. The negatively charged body *A* and the positively charged sphere *B* now *attract* each other in order to produce, if possible, a neutral condition.

In Fig. 2*b* the effect is shown of bringing near to *C* a *larger* piece of paper, brushed briskly, and thus highly charged with electrons (−ve). Electrons now rush along the conducting wire *W* and crowd in excess on *B*

Fig. 2*c*



so that *B* is *negatively* charged: *repulsion* occurs between *A* and *B*, both being negatively charged; the stresses and strains in the ether are indicated by the dotted "lines of force." Quickly lift off the wire *W* by means of the glass rod *R* (Fig. 2*c*). *A* and *B* still repel each other, and on replacing *B* by *C* there is a stronger attraction between *A* and *C* than when the uncharged spheres were used as shown in Fig. 2*a*. Next bring *B* and *C* into contact and note that together they attract *A*, just as any other *uncharged* body does.

This method of charging the two spheres respectively (1) with excess of electrons (negatively), (2) with electrons in defect (positively) is called **induction**: *D* is called the *charging body* (in this case *negative*); an *opposite* charge is **induced** at the *near* end of the insulated system and a *like* charge is induced at the *remote* end. The two opposite charges neutralize each other, for on removing *D*, the insulated system is still uncharged. This shows that *two equal* but *opposite charges are induced at the same time.*

Additional Exps. A. Try the effect of substituting for the electrified paper (*D*) the following:

(1) *Sealing wax* rubbed with *flannel.*
(2) *Glass* ,, ,, *silk.*

(i) The *sealing wax* behaves as the paper did, but more markedly—electrons are in excess on the sealing wax; it is *negatively* charged. (ii) The *glass* is positively charged.

B. Repeat the experiments, placing charged rods of sealing wax and glass successively in the stirrup, and substituting for *D* other charged rods of sealing wax and glass. Record your observations carefully and make your own deductions.

7. The Electroscope is an instrument for detecting the presence and nature of small charges of electricity. It may be readily and inexpensively made by the students themselves. It consists of an insulated brass strip or thick wire AB, bent in the form shown in Fig. 3. A brass knob (K) *or* an open metal can (C) may be fitted to the end A. At F a flange is soldered. At the bend D a strip of gold or aluminium leaf (G) is attached by a thin coating of seccotine, care being taken to preserve metallic contact between the rod and the leaf. The leaf of the electroscope is protected from draughts by supporting it in a glass bottle, the metal rod $AFDB$ being held by the flange which rests on an insulating plug of paraffin wax or on a half-split cork previously well soaked in melted paraffin wax[1]. The instrument is rendered more sensitive by cementing a strip of tin-foil TT_1 on the outside and bottom of the glass vessel, opposite to the leaf (G).

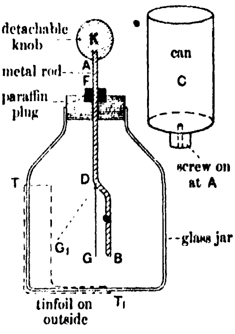


Fig. 3.

Exp. (i) **To charge the electroscope with excess of electrons** (*i.e.* **negatively) by contact.**

(1) Touch the knob (K) by (a) warmed paper that has been brushed with a warm dry brush; (b) a stick of ebonite or sealing wax rubbed with flannel: or

(2) Replace the knob (K) with the can (C) into which may be placed the brushed paper or the rubbed sealing wax. The insulated metallic part of the electroscope is now charged with excess of electrons and, as they repel each other, the light leaf (G) tends to fly away from the rod DB: the electroscope is said to be *charged negatively*.

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[1] The insulation by means of paraffin wax must be as perfect as possible: it is well too to coat the glass inside and out with shellac varnish (paint or wash with shellac dissolved in methylated spirit) which prevents the deposit of a thin film of moisture on glass.

"**Earthing.**" Notice that if we touch the electroscope the leaf falls; it is said to be *discharged* or **earthed,** *i.e.* connected to the earth. We may consider the Earth to be a huge mass of neutral atoms into which electrons may escape from a negatively charged body or from which electrons may be drawn to any extent without affecting the neutral condition of so large a quantity of atoms. Compare "**sea-level**" with this neutral "**earthed**" condition; water pumped into or out of the sea does not materially affect the level of the ocean: similarly the earth is a huge reservoir whose neutral condition is not affected by addition or removal of electrons.

Exp. (ii) **To charge the electroscope by induction.**

(i) **Positively.** Having "earthed" the electroscope by touching it, bring near to the knob (*K*) a rod of sealing wax or ebonite previously charged with electrons (**negatively**) by friction with flannel. The leaf (*G*) rises because a certain number of "free" electrons are repelled into it, leaving the region near *K* with a defect of electrons, *i.e.* positively charged. (Fig. 4.) Now touch *K* with the hand, thus "earthing" a number of electrons corresponding to those that were driven into the remote parts *GBD*. Remove, firstly, the hand, secondly the rod: the remaining "free" electrons now distribute themselves uniformly over the *metal* of the electroscope, which having a defect of electrons is **positively** charged.

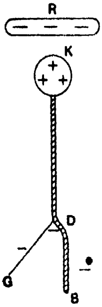

Fig. 4.

(ii) **Negatively.** We must substitute for the sealing wax rod above a **positively** charged rod, *e.g.* glass rubbed with silk. Try this, and also the effect on the leaf of bringing (1) positive, (2) negative charges near *K* when the electroscope is charged (*a*) positively, (*b*) negatively. Record and explain your results.

8. Exp. To show that when electrons are separated from atoms the latter constitute an equal but opposite quantity of electricity.

We must constantly bear in mind that when "electricity is generated," no new substance is created—it is merely the act of *separation of electrons from their atoms.*

An electroscope, provided with a can (Fig. 8) or connected to an insulated can, is first used uncharged.

An ebonite rod *R*, fixed in a clamp (Fig. 5), is then fitted with a flannel cap which may be rotated round the rod by pulling alternately two insulating silk threads wound in opposite directions round the cap. By the work done in overcoming friction, electrons are separated from atoms and these electrons congregate on the ebonite, but are not separated widely from the corresponding positive nuclei on the flannel until the cap is removed. Place the two (cap and rod), before separating, into the can of the electroscope: combined they show no charge. Next pull off the cap by the insulating silk thread and show by the electroscope (previously charged $+^{\text{vely}}$) that each is charged with electricity, but the cap $+^{\text{vely}}$ and the rod $-^{\text{vely}}$. Then place the cap, by holding it with the silk thread, into the can of the uncharged electroscope—the leaf rises; and lastly put the ebonite rod into the can as well as the cap—the leaf falls. Make your deductions in each case.

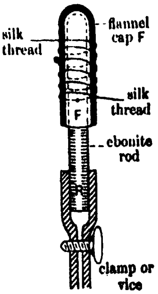

Fig. 5.

9. Relation between inducing and induced charges. (Faraday's Ice-pail Experiment.)

We have already shown in § 6 that, when a charged body is brought near an insulated conductor, **two equal but opposite charges are separated by induction** on the conductor. This may also be proved by means of the electroscope fitted with a can (*C*) and at the same time that each **induced charge is equal to the inducing charge** when the body holding the inducing charge is practically surrounded by the insulated conductor. Incidentally we can also show that **the charge resides on the outside of an insulated conductor.** This latter statement naturally follows from the property of electrons, viz. that they **repel each other.**

Exp. Discharge the electroscope by touching it ("earthing" it). A brass ball, insulated by suspending it with a silk thread, is charged *negatively* (say), *i.e.* with electrons, by touching it with brushed paper or ebonite (or sealing wax) rubbed with flannel.

(i) Lower the $-^{\text{vely}}$ charged ball (*B*) into the can[1] (*C*) but *without touching* it (Fig. 6): the leaf rises with the induced charge of electrons. On removing the ball the leaf falls, showing that the electroscope is still uncharged (*i.e.* neutral). Lower the ball again into the can and let it *touch* the bottom: the leaf has risen, but it rises no farther when contact takes place: remove the ball and show by means of a second electroscope that the ball is now *uncharged*, *i.e.* its electrons have neutralized the equal but opposite quantity of electricity *induced*, or summoned, on the inside of the can opposite the ball. Also, since the ball on removal from the inside of the can is found to be uncharged, it is evident that the electrons have repelled each other to the *outer* limits of the insulated conductor.

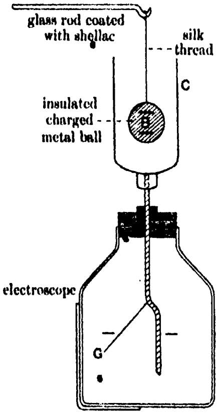

Fig. 6.

(ii) Again lower the $-^{\text{vely}}$ charged ball into the can, but do not let it touch the can: the leaf rises with the induced charge of electrons: touch the can momentarily with the finger—the leaf falls: withdraw the ball without allowing it to touch the can—the leaf rises: next allow the ball to touch the can—both the *ball* and *can* are now found to be *discharged*.

A restatement of the deductions from these experiments is useful:

(*a*) A charged body brought near an insulated conductor causes a separation of electrons from atoms by induction.

(*b*) Electrons are repelled from or attracted to the inducing body according as the latter is charged $-^{\text{vely}}$ or $+^{\text{vely}}$.

---

[1] The experiment is often called "**Faraday's Ice-pail Experiment,**" because the can originally used by Sir Michael Faraday, when he first demonstrated these facts about the year 1830, was an insulated ice-pail connected to an electroscope by a wire.

(*c*) The inducing and induced charges are equal, but of opposite sign, and together they neutralize each other.

N.B. The can or "ice-pail" is supposed practically to surround the charged insulated ball.

(*d*) The charge resides on the outer surface of a conductor.

10. Recapitulation to assist in visualizing the "Electric Current."

The results of recent discovery enable us to gain some insight into the properties of conductors of which the best are pure metals [see Table, § 3]. It is now believed that electrons move freely among the atoms of metals. If we could isolate a single neutral atom of a metal, we should probably find that its electrons (numbering to nearly 100 according to the **atomic number** of the particular metallic element considered) revolve in paths round a nucleus. We may imagine that the atom is not solid matter, but a system of matter arranged in some mathematical form, the motion of the electrons in their orbits being comparable to that of the planets in the solar system. In an aggregate of atoms composing the metal, the spaces between the particles may be considered to be very great, so that electrons may pass somewhat freely through the atoms without more than slight probability of collision either with the nucleus or with the satellite electrons. We can further imagine that one or more electrons may fly off or be removed from an atom and travel for some distance, passing through several atomic systems before colliding with or attaching themselves to other atoms, much in the same way as comets pass right through our solar system or are absorbed into it. We can also imagine that as electrons are added to an insulated conductor, there is immediately an "increase of pressure," of electrons throughout the whole metal; and that if now the conductor is "earthed," by touching it with a wire held in the hand, electrons flow along the wire to the earth until the pressure is restored to the normal or neutral condition. We call this flow of electrons through the metal an *electric current.*

QUESTIONS ON CHAPTER I

1. Criticize the statement "Electricity is a form of Energy." Mention various types of energy and describe briefly how they are mutually convertible.

2. Define element, atom, electron.

What do you mean by the statement that a body is electrically charged, and how would you show in a simple manner the existence of two kinds of electricity?

3. What are the fundamental facts of attraction and repulsion of electric charges, and describe any experiments you would perform to illustrate them?

If electricity of one kind is produced, how would you show that an equal quantity of the opposite kind is produced at the same time?

4. A piece of ebonite is rubbed with flannel and then brought near to some small pieces of paper. Explain, on the Electron Theory, the charging of the ebonite and the subsequent behaviour of the pieces of paper.

5. Define conductor and insulator.

Make a list of the common substances in the room in the order of their conductivity.

6. What is an electroscope? What special precautions would you take, in constructing one, to prevent leakage of electricity?

7. Devise practical experiments (*a*) to electrify a brass tube by friction, (*b*) to test whether its charge is positive or negative, (*c*) to show there is no charge inside the tube.

8. How would you charge an electroscope (*a*) positively, (*b*) negatively, using a glass rod?

9. Explain the term "induction." Two exactly similar electroscopes have their caps connected by a wire and a positively charged body is brought near the cap of one of them. Compare and explain their indications.

If the wire be now removed by means of an insulating handle, and then the charged body be also removed, what effects will be observed in the electroscopes?

10. Describe carefully Faraday's Ice-Pail experiment, illustrating the various stages of the experiment by diagrams showing the kinds of electrification produced. Carefully tabulate your conclusions.

11. An earthed conductor is held near a charged hollow conductor. In what position must it be placed to obtain the greatest induced charge?

CHAPTER II

HYDROSTATIC RELATIONSHIP BETWEEN CURRENT, PRESSURE AND RESISTANCE. THE ELECTRIC CELL

11. In § 4 we called the force that drives electrons in a definite direction through a conductor an **electromotive force**, the difference in pressure exerted by electrons in various parts of the conductor we called **difference of potential**[1], and we drew an analogy between *electric* and *hydrostatic pressure*. Let us now try **to find** by experiment whether, when water flows through a tube, there is any **relationship between the** (1) **Current,** (2) **Difference of Pressure and** (3) **Resistance** in the tube.

Demonstration. We *measure Current* [C] by the quantity of water delivered in a definite time $\left[\frac{Q}{t}\right]$.

We *measure Pressure* [P] at a point in the tube by the vertical height of a column of water at that point.

And we can *alter Resistance* [R] by (a) varying the cross-sectional area [A] of the tube, (b) varying the length of the tube

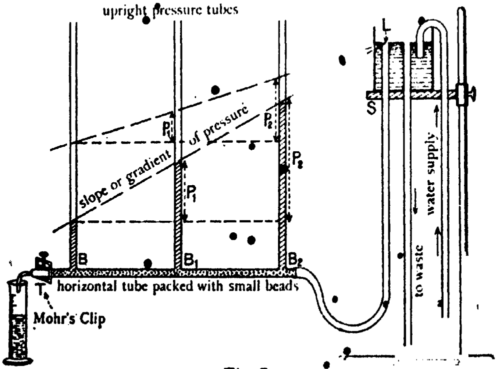

Fig. 7.

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[1] For strict definition, see § 79.

[L], (c) altering the packing in the tube, *e.g.* small glass beads, sand, glass wool, where resistance depends on the qualities of each particular substance [K].

Set up the apparatus as shown in Fig. 7 which explains itself. B, B_1, B_2 is a *horizontal* glass tube (150 cms.) tightly packed with small glass beads and connected to a cistern where water is maintained at a constant level. The outflow of water is regulated by the tap T. At B, B_1, B_2 vertical glass tubes are fused on to the main tube, the pressure being measured by noting the heights of the water-columns, differences in level indicating differences in pressure:

thus, P_1 measures the difference in pressure between B and B_1
and P_2 ,, ,, B_1 and B_2.

We notice that when the *current is steady*, *i.e.* when the tap T is adjusted so that *equal quantities flow in equal times*, the *tops of the columns* are in *one straight line*, which itself indicates the *slope* or gradient of pressure of the water within the tube. We *vary the pressure* gradient by *raising* or *lowering* the shelf (S) thereby altering the "head of water."

The following table gives the result of a series of observations of pressure and current.

Observation	**Pressure** (P) = difference in press. between points B and B_2 as measured by difference in heights of water-columns	**Current** (C) = vol. of water delivered in 5 mins., the gradient of pressure remaining constant during the time $C=\frac{Q}{t}$	Ratio $\frac{\textbf{Pressure}}{\textbf{Current}}$ = Constant $\frac{P}{C}=k$
1.	26·0 cms.	340 cc. per 300 secs.	$\frac{26}{340}=0{\cdot}76$
2.	28·7 ,,	390 ,, ,,	$\frac{28{\cdot}7}{390}=0{\cdot}74$
3.	29·0 ,,	400 ,, ,,	$\frac{29}{400}=0{\cdot}73$
4.	31·0 ,,	430	31

Let us examine these observations to find whether there is any simple relationship between *Pressure* and *Current*, the *Resistance*[1] of tap and tube, when once adjusted, being kept *constant.*

From this experiment we make the deduction that, *assuming the Resistance to be constant*, the **Current is proportional to the Pressure** difference.

Resistance. If the tap T is opened or closed slightly, the resistance is correspondingly lessened or increased.

Exp. Take another series of observations, having altered the Resistance. The above constancy of relationship $\left(\frac{\text{Pressure}}{\text{Current}}\right)$ still holds good, but the ratio P/C varies with rise or fall of the Resistance.

We may therefore use this ratio as a measure of the resistance, and we shall define **resistance** as the **ratio of pressure difference to current** provided that the conditions remain constant. Hence

$$\frac{\textbf{Pressure Difference}}{\textbf{Current}} = \textbf{Resistance.}$$

12. A Closed Circuit. In the experiment we have just performed we allowed the water to run to waste; we might, however, have maintained the pressure by returning the water flowing out through T to the water in the cistern L, either by (*a*) actually *lifting* the outflowing water to the higher level or (*b*) *working* a pump in a tube joining the out-flow and in-flow cistern. In each case **work** must be done to maintain the flow. If the water used is contained in

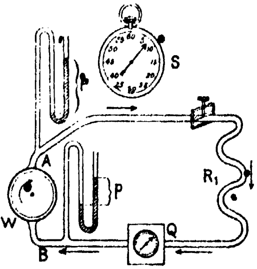

Fig. 8. Q, Water Meter. W, Centrifugal Pump. S, Stop-watch registering time in seconds (t).

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[1] It is extremely difficult to maintain a constant resistance if the current is varying; cross currents and eddy currents set up between the beads interfere with the main current: good results are obtained provided that the beads are very small and variations of pressure are not too great.

one continuous tube, the system is called a **closed circuit**, and may be diagrammatically shown as in Fig. 8.

The Pressure Difference $(P-p)$ is maintained by the centrifugal pump, which is working at such a rate that W units of work (say) are performed by the current, between A and B in the *external* circuit, in t secs. The **quantity** of water Q passing through the circuit is measured by the meter: the current (C), *i.e.* quantity per unit of time $= \frac{Q}{t} = C$.

Then (1) $\dfrac{\text{Pressure Difference}}{\text{Current}} = \dfrac{P-p}{Q/t} = R_1$,

where R_1 = resistance of external circuit between A and B.

(2) Work done (W) = Quantity × Pressure Difference $= Q(P-p)$.

(3) Power of the external circuit = Rate of doing work

$$= \text{Work done per unit of time}$$

$$= \frac{Q(P-p)}{t} = C(P-p)$$

$$= \text{Current} \times \text{Press. Difference}^1.$$

Important Note.

> The pressure difference between A and B, *i.e.* $(P-p)$, will not measure the real pressure (E) exerted by the pump, as this pressure difference will act in the opposite direction to E within the pump. In addition the pressure E will have to overcome the internal resistance of the pump. Hence
>
> $$\frac{\text{Actual Pressure exerted by pump}}{\text{Current}} = \frac{E}{Q/t} = R_1 + r,$$

where r = internal resistance of pump.

13. A Closed Electric Circuit.

If in Fig. 8 we substitute:

(*a*) for the *pump* an **electric cell** or battery of cells [see § 19], a *dynamo*, or other generator of an electric current;

(*b*) for the *tube* a **wire** or system of wires, electric lamps, electro-magnets and motors connected by wires [external circuit];

---

[1] Cf. Watts = Ampères × Volts [§ 80].

(c) for the *pressure gauge* an instrument called a **voltmeter** [see § 66], which measures difference of electric pressure, *i.e.*, **potential difference** [P.D.] or **voltage,** in units called **volts;**

(*d*) for the *water meter* an instrument called an **ammeter** [see § 47], which measures electric **current,** *i.e.* quantity of electricity passing a point per sec., in units called **ampères;**

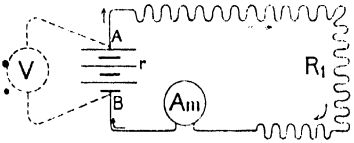

Fig. 9. *AB*, Battery of Cells or Generator of Electricity. *Am*, **Ammeter,** measures the Current in **Ampères.** *V*, **Voltmeter,** measures the P.D. in **Volts.** R_1, **Resistance** of the circuit, apart from the Battery, in units called **Ohms**; *r*, **Resistance** of the Battery in **Ohms.** $R = R_1 + r =$ **Total Resistance** of the circuit in **Ohms.**

and if we called the external **resistance** of the circuit $\mathbf{R}_1$, measured in units called **Ohms,** we can draw another diagram (Fig. 9) and continue the analogy between fluids and electricity still further. In addition we shall find that the relationship between *pressure, current* and *resistance,* which under certain limitations holds good in hydrostatics, may be generalized for electricity in the form of a law [**Ohm's Law**].

In § 11 we established the *hydrostatic* relationship

$$\frac{\text{Pressure Difference}}{\text{Quantity delivered in unit time}} = \text{Resistance},$$

$$i.e.\ \text{Current} = \frac{\text{Pressure Difference}}{\text{Resistance}};$$

which in *electric* terms becomes

(i) for the *external* part of circuit between *A* and *B*

$$\text{Current} = \frac{\text{Potential Difference}}{\text{Resistance}} = \frac{\text{P. D.}}{R_1};$$

(ii) for whole circuit (see note, end of § 12)

$$\text{Current} = \frac{\text{Electromotive Force of Battery}}{\text{Total Resistance of Circuit}} = \frac{\text{E.M.F.}}{R_1 + r} = \frac{E}{R},$$

where R_1 = resistance of external circuit,
r = „ internal „
$R = R_1 + r$ = total resistance of circuit.

This equation expresses OHM'S LAW which states that the *current* in a circuit varies directly as the *electromotive force* (E.M.F.) and inversely as the *Resistance* of the circuit.

Important Note (cf. p. 18).

If a current is flowing through the cell and an external circuit, the E.M.F. of the battery is *NOT* equal to the P.D. between the plates of the cell; as this P.D. and the E.M.F. will work against each other inside the cell.

If, however, the cell is on "**open circuit,**" *i.e.* no current is flowing through the cell, the E.M.F. of the cell is equal to the P.D. between its plates.

Let us now describe the instruments mentioned in the last paragraph, and at the same time explain, as far as is possible at this stage, the terms used and note also the various effects of the electric current.

14. Electric Cells.

The Voltaic Cell [Volta—Italian physicist 1745–1827].

A rod of **pure Zinc** and a strip of **Copper** foil (Fig. 10*a*) to which wires are attached are placed in a beaker of dilute Sulphuric Acid [1 part acid to 9 parts water], great care being taken that no metallic contact takes place between the Zinc and the Copper either inside or out of the acid. No effervescence takes place. Touch the ends of the wires together and also connect them through a suitable ammeter (Fig. 10 *b*) and note that—

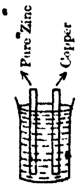

Fig 10 *a*.

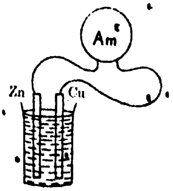

Fig. 10 *b*.

(*a*) the ammeter records the passage of an electric current;

(*b*) bubbles of hydrogen appear on the copper foil

This arrangement of Zinc and Copper plates in a vessel containing dilute sulphuric acid is called a simple Voltaic cell.

Exp. To show that in a Voltaic Cell (Fig. 11)

(i) **electrons accumulate on the Zinc plate,** which consequently becomes $-^{vely}$ charged and

(ii) the Copper foil becomes $+^{vely}$ charged.

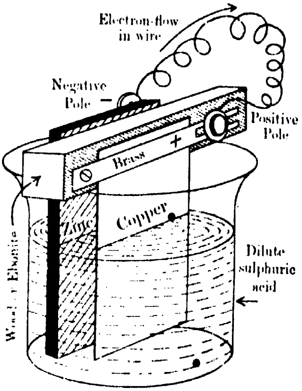

Fig. 11. Voltaic Cell.

In our experiments on the voltaic cell no *chemical* action is observed to take place when a zinc plate and a copper plate are placed, without metallic contact, in a dish containing dilute sulphuric acid. But a very important *electrical* change had taken place which can be verified by experiment, viz. that owing to a partial solution of the zinc, electrons have accumulated on the zinc plate, causing a *pressure difference* between the zinc and the copper. This pressure difference (about 1·08 volts) corresponds to the pressure exerted by the centrifugal pump in § 12. On *completion of the circuit* by a copper wire a current of electrons flows from the zinc to the copper along the wire, returning by way of the solution. This pressure difference, which exists even whilst the circuit is incomplete, is known as the **Electromotive Force (E.M.F.)** of the cell when on "open circuit," and is a measure of the "driving power" of the battery.

The energy necessary, to produce the electron-flow (current) when the circuit is completed is provided by *chemical action* within the battery (in the voltaic cell by the solution of zinc in sulphuric acid).

Note on **amalgamation** and **local action.**

Commercial zinc is used in batteries because it is much less expensive than *pure* zinc. The *impurities* found in commercial zinc are carbon and arsenic in minute granules, which in contact with zinc act as the copper did when the plates were joined in the voltaic cell. This contact or coupling of zinc with carbon (say) causes immediate solution of the metal. This *local action*, as it is called, may be prevented by covering the zinc plate with a layer of mercury which is effected by *scrubbing* the plate *with a mixture of mercury and dilute sulphuric acid.* Mercury dissolves zinc, but not the impurities, and forms an **amalgam,** so that *pure* zinc is presented to the acid solution in the battery: the zinc plate is then said to be **amalgamated,** and no general solution of the metal takes place, except when the circuit is completed.

Demonstration. A single voltaic cell does not possess sufficient E.M.F. for the purposes of this experiment: we must multiply the pressure by linking a dozen or more cells **in series,** *i.e.* by making a chain or series of cells (Fig. 12) in which the copper foil of any cell of the series is joined to the zinc plate of the next cell, so that the E.M.F. of each cell in the succession is added to that of its neighbour. Thus if **E** represents the E.M.F. of one cell in a battery of **n** cells joined "in series," the **total E.M.F = nE.**

In order to collect a large number of free electrons from the zinc or negative pole of the battery, the terminal is connected by a wire X to the lower part of a **condenser** D joined by a wire W to an electroscope. If the lower plate of D actually forms the plate of the electroscope S, the instrument is called a **condensing electroscope.** A condenser is a kind of reservoir for electrons: it consists of *two large flat plates of metal* (brass) separated and insulated from each other by a piece of *paraffined paper*, the lower plate being supported on an insulating stand; the larger the area of the plates the larger the **capacity** of the reservoir or condenser becomes, and the capacity is still further increased by "earthing" the upper plate. [Attach the wire, Y, to the gas pipe.] In Fig. 12 the condenser is shown in vertical section, the upper plate being joined to the copper ($+^{ve}$) pole by the wire *Y*, and the lower to the zinc ($-^{ve}$) pole, and to the electroscope as described above. Electrons flow into the lower plate of *D* which becomes negatively charged, and an equal but opposite charge is held bound by induction on the upper plate. (1) Break contact with *X* (see Fig. 12), no change is seen in the electroscope until (2) the upper plate is raised, when (3) the leaf of the electroscope rises and is found to be charged negatively [see § 7], owing to the in-flow of electrons from the zinc pole of the battery.

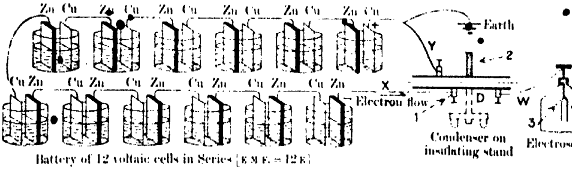
Zn
Cu
Earth
Y
2
X
Electron flow
D
W
1
3
Condenser on insulating stand
Electros
Battery of 12 voltaic cells in Series [E.M.F. = 12 E]

Fig. 12. 1. Touch here and break contact. 2. Raise top plate of condenser. 3. Note rise of leaf and that electroscope is negatively charged.

The cells in Fig. 12 are joined **in series.** Fig. 13 shows a battery of 3 voltaic cells joined **in parallel.** The term **in parallel** or *in multiple arc* is used when all the zinc plates of a battery are joined by wires, making virtually one large zinc plate; and, also, all the copper plates are joined thus increasing the size of the copper plate, the whole battery being now one larger cell of the same E.M.F. as before, but with less internal resistance to the passage of electrons [see § 16].

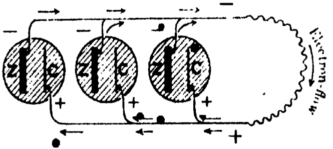

Fig. 13.

15. Terms and Conventions.

Unfortunately the term **positive** ($+^{ve}$) **pole** had been given to the terminal of the *copper* plate of the cell and the term

negative ($-^{ve}$) **pole** to the terminal of the *zinc* plate long before the existence of electrons and the electron-flow was known. These terms were assigned arbitrarily, and as a consequence the **positive direction of the current** in the wire **outside** the cell from $+^{ve}$ (copper) plate to $-^{ve}$ (zinc) plate was also determined on arbitrarily.

The **direction of the current** may be remembered by the mnemonic **"zINc,"** which indicates that **in** the cell itself the direction assigned to the current is from zinc to copper [or carbon] plate.

We now know that the actual **direction of the electron-flow is contrary to the** *arbitrarily chosen direction of* **current.** Electrons only flow from the $+^{ve}$ (copper) plate to the $-^{ve}$ (zinc) plate *within* the cell, *i.e.* in the solution.

16. Theory of the Voltaic Cell.

It is supposed that the molecules of pure sulphuric acid (H_2SO_4), themselves *neutral*, dissociate on being dissolved in water into two kinds of **ions** (from Greek = "goers" or "travellers") charged respectively positively and negatively. Thus one molecule of sulphuric acid dissociates into *two hydrions positively* charged, each with one electron (ϵ) in defect, and a *negatively* charged *sulphion* carrying two additional electrons. The dissociation may be represented thus

$$\underset{\text{neutral molecule}}{H_2SO_4} \rightleftarrows \underset{\text{positive ions}}{\begin{matrix}H-\epsilon\\ H-\epsilon\end{matrix}} \quad \underset{\text{negative ions}}{SO_4\begin{matrix}+\epsilon\\ +\epsilon\end{matrix}}$$

Using pure zinc and copper plates in the cell containing dilute sulphuric acid, no visible reaction occurs and no current flows, until the circuit is closed, when chemical action, necessary to maintain the electron-flow which produces the E.M.F., begins. The $-^{ve}$ sulphions, on touching the zinc, combine with it to form zinc sulphate ($ZnSO_4$), thus setting free their electrons, which are propelled by the pressure already mentioned through the zinc and along the connecting wire towards the copper plate,

$$\mathrm{Zn} + \mathrm{SO}_4{}^{+\epsilon}_{+\epsilon} = \mathrm{ZnSO}_4 + 2\epsilon.$$

In the meanwhile, in the solution adjoining the copper pl two hydrions, $2(H-\epsilon)$, for every sulphion combining v zinc, receive two of the freed electrons (2ϵ) and so becom molecule of neutral hydrogen (H_2); thus a stream of electı continues in the connecting wire and round the circuit as lon zinc dissolves.

17. Polarization. The accumulation of hydrogen round the copper plate impedes and even altogether prevents the passage of electrons. This process is called *polarization.* It is supposed that, when the hydrogen accumulates, hydrions do not at once give up their charges to the plate, but form a layer or as it were a new "plate" of positive electricity alongside the copper plate and prevent, by their repulsion, the arrival of further ions, thus constituting a new electric couple which tends to drive electrons *back*, *i.e.* in the opposite direction to the original flow caused by the solution of zinc. This **back E.M.F.** is chiefly responsible for the falling off of current; but polarization is also due to the insulation of the copper plate by the non-conducting bubbles of hydrogen that accumulate [p. 27].

To maintain a steady current, it is therefore necessary to *remove the hydrogen*, either by

(i) *mechanical* means, *e.g.* brushing with a camel-hair brush; or (ii) *chemical* means, *e.g.* adding to the battery solution a strong oxidizer, called the **depolarizer** [$2H + \hat{O} = H_2O$], such as chromic oxide (CrO_3). Nitric acid (HNO_3) and black oxide of manganese (MnO_2) are also used under certain conditions [§§ 18, 19] as depolarizers.

Demonstration to illustrate Polarization and the action of Depolarizers.

Two voltaic cells are connected "in series" by thick copper wire with (1) a "demonstration" *Voltmeter*[1] measuring electric pressure up to 3 volts; and

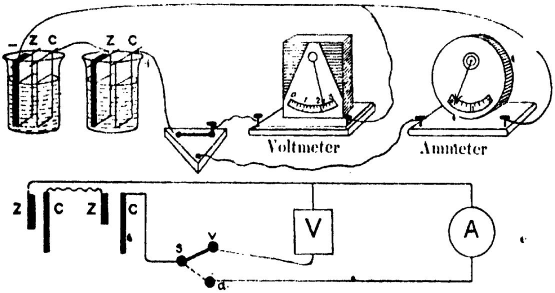

Fig. 14.

(2) a "demonstration" *Ammeter* measuring current to (say) 2 ampères.

The wires are arranged as in Fig. 14 so that by means of a "two way plug" or "switch" (Fig. 15)[2] (*a*) the voltmeter, or (*b*) the ammeter, may be included in the battery circuit. A voltmeter consists essentially of a coil of very fine wire presenting great resistance to the current and a magnet attached to the pointer: an ammeter is fitted with a coil of

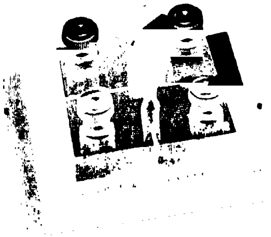

Fig. 15.

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[1] See that the $+^{ve}$ pole of the battery is connected to the $+^{ve}$ terminal of the voltmeter and of the ammeter.

[2] Fig. 15 is a plug commutator [see § 52], but it may be used as a "two way plug" by joining (say) the left-hand pair of terminals by the battery wire.

thick wire which allows electrons freely to pass round the circuit. (i) *Note* the *voltage* before the ammeter has been put into the circuit by joining *s* to *v*, then switch the current through *A* by joining *s* to *a*: a rapid falling off of current will be observed: record this and the time occupied. Then switch *V* in circuit and (ii) *note* also that the *voltage* has fallen considerably. Next, using a camel-hair brush, *remove the bubbles of hydrogen* that have collected on the copper plate and (iii) *note* the *rise* both in pressure and current. Finally short-circuit the battery once more through the ammeter until the current and voltage have fallen: then add to both cells a strong solution of *chromic acid* (a *depolarizer*): observe that the hydrogen bubbles soon disappear and that both voltage and current are restored to their original strength.

18. Single Fluid Cells[1].

(1) **The Voltaic Cell** [§ 14] E.M.F., Voltage or Terminal P.D. = 1·1 Volts app.

(2) **The Bichromate** (or **Chromic Acid**) **Cell** [E.M.F. = 2·1 Volts] consists of a **zinc** plate connected to one terminal (the $-^{ve}$ pole) and, on either side of the zinc, two **carbon** plates connected to a second terminal (the $+^{ve}$ pole) [Fig. 16]. These plates are immersed in dilute sulphuric acid in which crystals of potassium bichromate, or better still **chromic acid**, a strong oxidizer, have been dissolved and act as a **depolarizer**[2]. The zinc

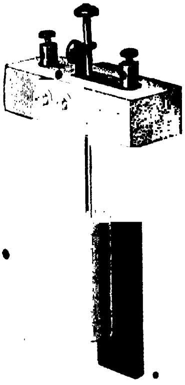

Fig. 16.

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[1] **Note to Demonstrator.** Separate specimens of each kind of cell may be set out round the laboratory and the students be allowed to move their positions in order to draw and describe the various cells in their note-books, and finally prepare a tabular statement under the following headings: name, E.M.F., $-^{ve}$ plate, excitant, $+^{ve}$ plate, depolarizer, remarks. Near each kind of cell should be placed a pocket voltmeter, French pattern, price 10*s*. 6*d*.

[2] For experiments with depolarizers see § 17.

plate when not in use may be lifted out of the acid solution by means of an adjustable rod. The solution should be made up in the following proportions: Sulphuric Acid 1 part, Chromic Acid 2 parts, Water 12 parts (or, if Potassium Bichromate is used, 4 parts).

Reactions. $Zn + H_2SO_4 = ZnSO_4 + 2\hat{H},$

$$6\hat{H} + 2CrO_3 = Cr_2O_3 + 3H_2O,$$

$$Cr_2O_3 + 3H_2SO_4 = Cr_2(SO_4)_3 + 3H_2O.$$

(3) **The Leclanché Cell** [E. M. F. = 1·4 Volt] gives a small current, useful for electric bells and telephones, and may be used intermittently for many months provided there are intervals for the recovery from polarization. The cell (Fig. 17) contains a saturated solution of **salammoniac** ($NH_4.Cl$) with a **zinc** rod for the $-^{\text{ve}}$ plate and a **carbon** plate for the $+^{\text{ve}}$, the latter being surrounded with crushed gas-carbon and **manganese dioxide** as *depolarizer* either contained in a porous pot or as an agglomerate block held together with plaster of Paris.

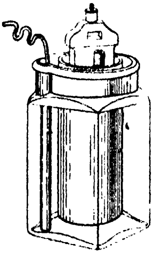


Fig. 17.

Reactions. $2NH_4.Cl = 2(\widehat{NH_4}) + 2\hat{C}l,$

$$Zn + 2(NH_4)Cl = ZnCl_2 + 2NH_3 + 2\hat{H},$$

$$2\hat{H} + 2MnO_2 = Mn_2O_3 + H_2O.$$

19. Two Fluid Cells.

(4) **Daniell's Cell** [E. M. F. = 1·1 Volts], shown in Fig. 18, consists of a rod (*a*) of **zinc** ($-^{\text{ve}}$) in dilute **sulphuric acid** (*b*) in a central porous pot (*c*) which prevents the mixing of the two solutions. The hydrogen ions travel through the porous earthenware towards the containing outer vessel of **copper** (*d*) which acts as the $+^{\text{ve}}$ plate and holds a solution of **copper sulphate** (*e*) replenished by a store of crystals placed on a perforated shelf (*f*). Polarization does not occur because the

hydrogen ions replace copper, which deposits on the copper vessel, from the solution.

Reactions.

$$Zn + H_2SO_4 = ZnSO_4 + 2\hat{H},$$
$$2\hat{H} + CuSO_4 = H_2SO_4 + Cu.$$

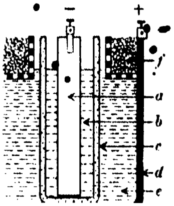


Fig. 18.

(5) **Grove's Cell** [E.M.F. = 1·9 Volts] contains a **U**-shaped **zinc** plate (− ^{ve}) in an outer flat jar holding dilute **sulphuric acid.** Fig. 19 shows a battery of 6 cells in series. Hydrogen ions make their way inwards through a flat porous pot in which is placed a sheet of **platinum** (+ ^{ve}) standing in strong **nitric acid** as *depolarizer.*

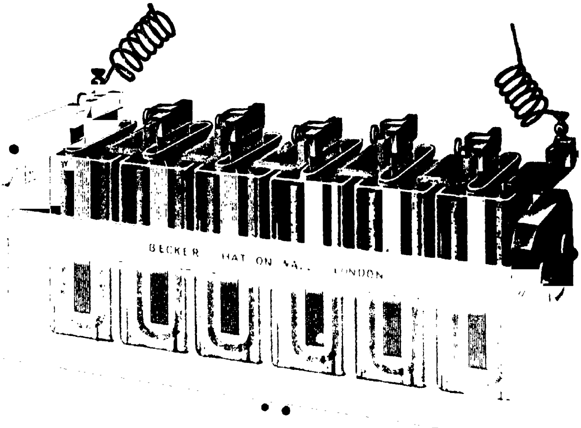


Fig. 19.

Reactions.

$$Zn + H_2SO_4 = ZnSO_4 + 2\hat{H},$$
$$4\hat{H} + 2HNO_3 = 3H_2O + NO\nearrow + NO_2\nearrow.$$

(6) **Bunsen's Cell** [E.M.F. = 1·9 Volts] is similar to Grove's except that a **carbon** plate is substituted for platinum as the +ve pole. The *drawback* of these cells (5) and (6) is that they emit eroding and irritating nitrous fumes through the process of depolarization.

Standard Cells.

(7) **Latimer Clark's Standard Cell** [E.M.F. = 1·433 Volts at 15° C.] is *never* used as a producer of current, but only in estimating the E.M.F. of another cell. It should never be used in closed circuit except with a very high resistance or when opposed by an almost equal E.M.F. [see Potentiometer, § 68]. The Clark's Standard Cell, Fig. 20, may easily be made by students in the Laboratory. The positive "plate" is a small quantity of **mercury** placed at the bottom of a boiling tube and connected to the +ve pole by a platinum wire contained in a fused glass tube. A paste of **mercurous sulphate** is placed on the mercury and on this stands a saturated solution of **zinc sulphate** into which dips the negative element, an amalgamated rod of **zinc.** A cork holds the rods in position and the tube is sealed with paraffin wax or marine glue.

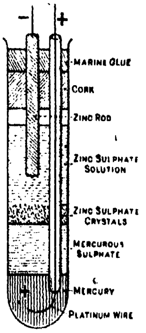
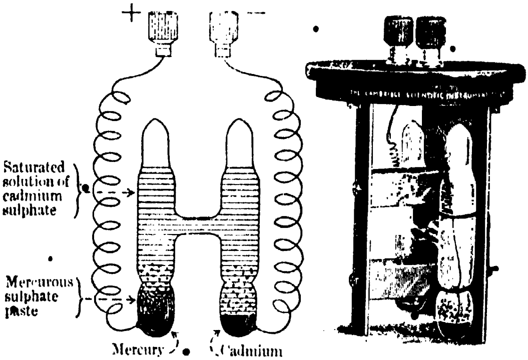


Fig. 20.

(8) **Weston's Standard Cell,** constructed on the same principle as Clark's, is also used *only* for comparison of E.M.F. in series with a very high external resistance. Cadmium amalgam replaces the zinc rod (−ve) [Fig. 21]. A saturated solution of cadmium sulphate fills the connecting tube between the two limbs and enables electrons to travel from the mercury (+ve) at the bottom of the left-hand limb. The International Conference on Electrical Standards adopted this under the name "Weston Normal Cell";

its E.M.F. = 1·0813 Volts at 20° C. which rises or falls 0·0000406 Volt per degree below or above 20° C.



Metal case removed.

Fig. 21. Weston Normal Cell.

(9) **Secondary Batteries, Storage Cells** or **Accumulators** (Fig. 22) [E.M.F. = 2·2 Volts] (see § 64) are now in general use for house installations, in laboratories[1], on motor cars and in various manufacturing processes where a steady current of moderate voltage is required. They are charged directly or indirectly from a dynamo. Current should only be taken from storage cells through a fairly high resistance; *short-circuiting, i.e.* joining the opposite terminals without adequate resistance between them, *must be always avoided*;

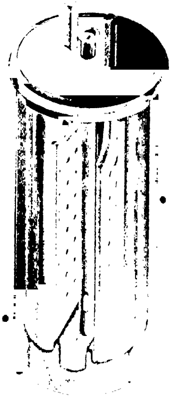


Fig. 22. Small Storage Battery.

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[1] Small Storage Cells are supplied by Messrs Pye & Co. of Cambridge.

any rapid reversal of the chemical action of charging the cells causes a buckling of the plates and destroys the battery.

The $+^{ve}$ *pole* of an accumulator is usually painted *red.*

For description and reactions see § 64.

QUESTIONS ON CHAPTER II

1. Describe an experiment to show the effect of pressure difference on the amount of liquid flowing through a horizontal straight glass tube.

Supposing a constant pressure difference be maintained between the ends, what do you think will be the effect of

(*a*) doubling the cross-section area of the tube,
(*b*) doubling the length of the tube,
(*c*) halving both the cross-section area and the length of the tube?

2. What constitutes a simple voltaic cell? Describe and account for the chemical and other changes (if any) which occur

(*a*) before, (*b*) after, joining the plates by a wire.

3. What is meant by (*a*) local action, (*b*) polarization? Describe fully the steps you would take to eliminate their effects.

4. What is meant by the E.M.F. of a cell? Is there any difference between the E.M.F. of a cell and the potential difference between the plates? In what units is the E.M.F. usually measured and from whence is the energy derived to maintain its value when the current is flowing?

5. Describe the Leclanché cell, with sketch, and show what method is used to overcome the effects of polarization within the cell.

6. With reference to a Daniell's cell state

(i) the part played by the copper sulphate,
(ii) the source from which its electrical energy is derived.

7. State Ohm's Law. In what units are current, pressure difference and resistance usually measured?

A voltaic cell of E.M.F. 1·5 volts is passed through an external resistance of 1 ohm. If the resistance of the cell is half an ohm, what is the current passing through the circuit?

8. The current from a battery of E.M.F. 2 volts and of ½ ohm resistance is sent through a coil of wire of resistance of 1½ ohms. What is the P.D. between its poles? If the resistance of the coil is 40 ohms, what effect will this have on the P.D. between the plates of the cell?

CHAPTER III

MAGNETISM

20. Historical. The fact that an ore rich in one of the **oxides of iron,** called **magnetite** from its occurrence in large quantities in the Roman province of Magnesia, attracts pieces of iron, was known to the ancient Greeks and is mentioned by Homer (B.C. 1000 *c.*) and Aristotle. Magnetite is described by Lucretius (B.C. 60 *c.*) who remarked that a chain of small pieces of the metal, iron, stick together when in contact with the mineral [magnetic induction, § 23].

That this stone suspended in air sets in a definite direction—approximately with its main axis North and South—appears to have been first noted in Europe about 1200 A.D., although the Chinese are credited with a much earlier knowledge of the fact. Consequently this stone was called a leading or **lodestone**; and mariners used it for directing their course in navigation. Later it was noticed that needles of steel, hardened iron containing about 1 $^{\circ}/_{\circ}$ carbon, after being rubbed in one direction along the lodestone, retained not only this property of setting in the N. and S. direction, but also the *power of attracting iron* which we call **Magnetism.** The *Mariner's Compass* was the outcome of these discoveries.

In the 16th century Robert Norman (1581) first observed that if the magnetized needle were balanced at its centre of gravity, the **north-seeking** end or **pole** tended to **dip** or *incline* downwards. About 1600 William Gilbert suggested that this dipping was due to the fact that the Earth itself is a magnetized sphere [§ 26], the theory being confirmed later by observations of the *angle of dip* at various latitudes.

In 1634 it was found that the compass needle at a particular place did not point in the same geographical direction as had been observed some years earlier [§ 21]. Furthermore, from combined magnetic and astronomical measurements this **variation** or *declination* of the magnetic N. and S. line from the true or geographical N. and S. line was also found to change as the *longitude* of the point of observation was changed—a fact of the utmost importance to seamen [§ 26].

Exps. (i) Suspend horizontally (*a*) a horse-shoe magnet, and (*b*) a bar magnet by means of a paper stirrup and pin fastened by fine thread to two wooden stands placed some distance apart (Fig. 23 *a*). Note that they set in the N. and S. direction, *i.e.* in the plane of the **Magnetic Meridian** for the place. Mark the N-seeking end or **North Pole** with gummed paper.

(ii) Remove the magnets entirely. Gum a piece of paper at one end of *two unmagnetized pieces of thickish wire* (*a*) of soft *iron*, (*b*) of *steel* (a knitting needle). Using two wooden stands, suspend each in a stirrup as in Fig. 23 (*b*). Notice that (1) they set in no definite direction and (2) there is no attraction or repulsion between the two wires.

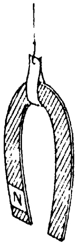


Fig. 23 (*a*).

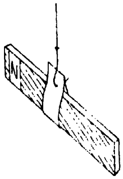


Fig. 23 (*b*).

(iii) Taking hold of the papered ends of the two wires laid side by side, draw the bar magnet several times in *one* direction along them so that the unpapered ends of the wires last touch the papered (N) end of the bar magnet (Fig. 24).

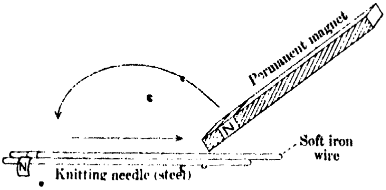


Fig. 24.

Now suspend separately the two wires. *Observe* that (1) the **soft iron** (*a*) sets in no definite direction, (*b*) is attracted at both ends by either pole of the bar or horse-shoe magnet; in short, the *soft iron does not remain magnetized.*

(2) the **steel** wire sets in the N. and S. direction the papered end being the N-seeking pole, and on bringing near the N-seeking end (N-pole) of the bar magnet, we observe that the N-pole repels a N-pole; we also find that two S-poles repel each other, but that N- and S-poles attract each other.

The first Law of Magnetic Force.

"*Like poles repel – unlike attract*" [cf. § 6 (2)].

(iv) Confirm this statement using suspended bar and horse-shoe magnets.

(v) Show by using a suspended magnet and two pieces of steel, the one magnetized and the other unmagnetized, that "*repulsion* between the steel and the suspended magnet is the *only test of magnetization.*"

21. The Compass Needle.

Examine a small pocket compass (Fig. 25). The magnetic needle does not set itself in the true N. and S. line, as found from the position of the sun at mid day. The magnetic meridian in England is for the present at an angle of 15° (approx.) West of the geographical meridian. [**Angle of Magnetic Variation** or *Declination.*] A small arrow head on the compass dial marks the direction which must coincide with that of the N-pole of the magnet needle in order that the four cardinal points N., E., S. and W. of the dial may correspond with the respective *geographical* directions.

Fig. 25.

A more sensitive instrument (Fig. 26) consisting of a short magnetized rod poised on a fine point by means of an agate bearing and furnished with a long aluminium pointer at right angles to the magnet is used in experiments to be described later [see Magnetometer, § 33 and Galvanometer, § 45].

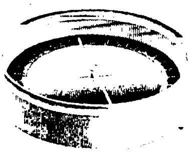


Fig. 26.

A **Mariner's Compass** is a modification of the single compass needle. Several small magnets are attached to a circular disc in such a position that (1) it balances at its centre, (2) the combined effect of the magnets is the same as that of a single magnet suspended at the centre of the disc. A card marked with degrees and the points of the compass (Fig. 27) is fixed on the disc so that the N. and S. line sets in the magnetic meridian. The disc can rotate with the minimum of friction round its centre of agate supported on a point of non-corrosible metal (iridium). The glass

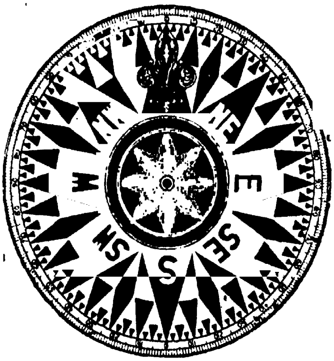


Fig. 27.

cover of the compass box has a line (the *lubber's* line), drawn diagonally over the centre of the rotating card and parallel to the ship's keel, by which bearings may be taken with the magnetic meridian.

22. Exp. To find the magnetic axis of an irregularly shaped magnet or a combination of magnets.

The following experiment exemplifies the principle of the Mariner's Compass and also the method of determining the position of the N. and S. line.

A cylindrical cork, through which two magnetized knitting needles have been fixed in parallel position NS, N_1S_1 (Fig. 28), with their *like* poles adjacent, is suspended by a fine thread attached to a wire HH_1 pushed along the axis of the cork. The combination of magnets so formed is hung from a wooden stand over a block covered with paper except over a large hole at the centre of the block. The suspension is adjusted so that the magnets are just clear of the paper. (1) The points $ABCD$ corresponding to NS, N_1S_1 are marked on the paper when the magnet combination has come to rest after swinging freely. (2) Taking care not to alter the position of support or paper, reverse the suspension by hanging the combination from hook H_1, marking off the points A, B, C, D, as before. (3) Remove the paper and transfer the trace of the magnets for positions (1) and (2) (Fig. 29) by pricking through the points to another piece of paper.

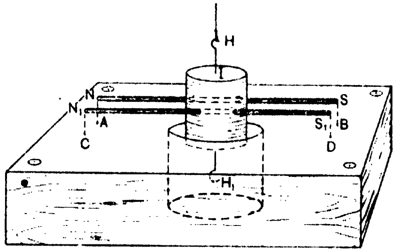


Fig. 28.

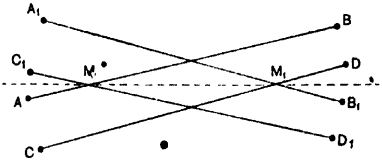


Fig. 29.

Complete the plan of the combination as shown in Fig. 29 and dot in the mean position by joining the points MM_1, which gives the **magnetic axis**, *i.e.* the line in the magnetic combination which coincides with the direction of the controlling magnetic force when the combination is allowed to swing freely to and fro and then come to rest.

Practical Exercise. Find the magnetic axis of a magnetized steel disc, pierced at its centre for suspension purposes.

An Astatic Combination.

Exp. Magnetize two knitting needles equally by holding them side by side and then stroke them in one direction along their length with one pole of a strong magnet. A *neutral or astatic combination* is obtained by reversing the position of one of the needles so that *unlike* poles are adjacent. The suspension may be either as in Fig. 28 *or* with the needles in the same vertical plane, Fig. 30, the latter arrangement being obtained by supporting the combination in a suitable stirrup.

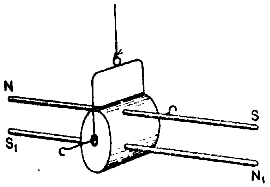
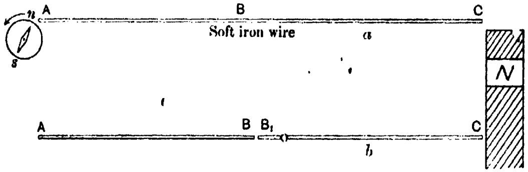


Fig. 30.

A perfect astatic combination sets itself in no definite position [cf. § 24, Exp. i (c)].

23. Induced Magnetism.

Exp. 1. Place a long piece of thick soft iron wire *ABC* on the bench in the E. and W. position and bring a small compass needle in the position shown in Fig. 31 *a*. Attraction takes place between



Figs. 31 *a* and *b*.

either end of the compass needle and the soft iron. Next bring the N-pole of a permanent magnet near the end *C* of the soft iron wire and tap the wire with a pencil. Repulsion of the N-pole of the compass needle occurs showing that the wire has become magnetized and that *A* is a N-pole. Reverse the permanent magnet and show that *A* now becomes a S-pole. Remove the permanent magnet and hammer the wire briskly once or twice; it will be found that the latter has lost its magnetism and will be attracted by either pole of the compass.

Exp. ii. Having cut the wire in two at *B*, place the ends in contact (Fig. 31 *b*) and repeat the experiment. Cut the wire into shorter lengths and place them end to end and try whether a "like" pole is **"induced"** at the end of the wire remote from the permanent magnet.

Exp. iii. Try whether a "chain" of soft iron nails or tacks (Fig. 32) is magnetized by being touched at one end by a permanent magnet.

Exp. iv. Place the permanent magnet on the bench and over it lay a sheet of white paper. Sprinkle iron filings evenly over the paper and tap one corner gently with the pencil, the filings arrange themselves in chains along definite lines (Fig. 33). It may be assumed from the results of Exps. ii and iii that each particle of iron has become a magnet and has fitted itself to its neighbour so that unlike poles are in contact.

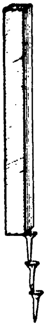


Fig. 32.

This conversion of an unmagnetized piece of iron to a magnet by the presence of a permanent magnet is called **magnetic induction** [cf. § 6]. The term will be extended later to include the effect of any magnetizing force on a magnetic substance. *Nickel* and *cobalt*, though to only a slight extent compared with iron, also show magnetic properties.

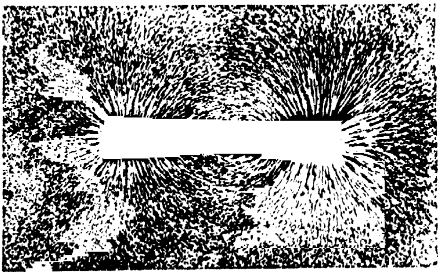


Fig. 33.

Practical Exercise.

Using a small compass, a long knitting needle (steel) and a bar magnet, show that, by *induction*, the feebly magnetized needle may have its magnetism (1) strengthened, (2) weakened, (3) neutralized and even (4) reversed by bringing near the permanent magnet. Carefully draw the positions to scale and note the effects (cf. Fig. 31 *a*).

24. Lines of Force and Mapping a Magnetic Field [horizontal plane only] by means of Iron filings.

Exp. 1. Using two short bar magnets, prepare **"filing maps"** of the following positions:

(*a*) the bars "end on," the N-pole of one about 2 inches from the S-pole of the second (Fig. 34), *i.e.* two **unlike** *poles adjacent*;

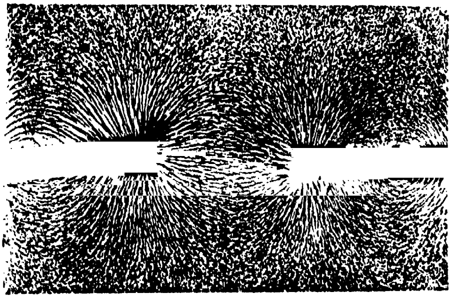
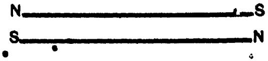


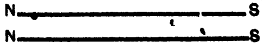
Fig. 34.

(*b*) ditto, but two **like** *poles adjacent* (Fig. 35);

(*c*) the two bar magnets parallel, *unlike* poles about 1½ inches apart



(*d*) ditto, but *like* poles opposite each other



Note. The "filing maps" may be made (1) on photographic paper (P.O.P.) which after exposure to suitable light may be developed or fixed in the usual way; or (2) on cartridge paper soaked in paraffin wax; the position of the filing-chains may be fixed by gently warming the wax by passing the Bunsen flame over it.

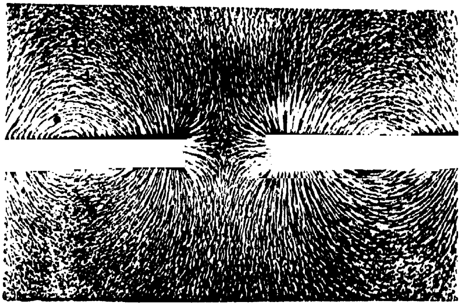


Fig. 35.

Exp. ii. Placing the bar magnets on a piece of paper on the bench in exactly the same positions as in Exp. i, find the direction in which a small compass needle (Fig. 25) sets when it is placed in various positions on the paper and compare the directions with those of the "filing maps" by marking a line between N- and S-poles of the compass needle on the paper.

Exp. iii. Mapping a horizontal Magnetic Field by means of a Compass needle.* (Fig. 36.)

(*a*) Remove all pieces of iron and all magnets except *one* bar magnet. Place this in the centre of an imperial sheet of cartridge paper on the bench, with the *N-pole* of the bar magnet *pointing N. in the magnetic meridian.* Place the compass on the paper near the N-pole of the bar magnet. Mark with a pencil on the paper the position in which the small needle sets. Follow the direction of its N-pole and obtain a series of positions as shown by the chain of small circles in Fig. 36. Join the successive positions by a *line* bearing an *arrow mark* which indicates *the direction in* *which a small north pole* tends to move under the combined influence of the magnetic forces (*a*) of the bar magnet, (*b*) of the Earth. Repeat from the other stations round the magnet and thus obtain a series of lines which map the **magnetic field of force** in the *horizontal* plane. These lines are called **lines of force.**

Observations. (1) The direction of the Earth's magnetic field is indicated by a small pointer at the top of the map.

(2) The Earth's magnetic force is strengthened by that of the magnet at the top and bottom of the map.

(3) These two forces exactly neutralize each other at points *P* and *P* (*neutral points*).

(4) The lines of the Earth's magnetic force bend inwards towards the magnet on the right and left of the map.

Exp. iv. Repeat (iii), reversing the position of the bar magnet (Fig. 37). Note the position of the neutral points *P*, *P*.

Exp. v. Map the lines of force when the magnet is placed in the E. and W. position.

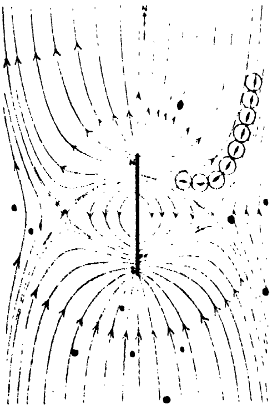


Fig. 36.

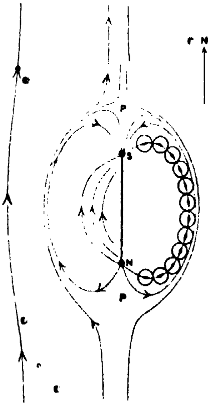


Fig. 37.

25. To find the true direction of the lines of force in a magnetic field.

In the last experiments it is necessary to bear in mind that we have been mapping the direction of the *horizontal component* of the magnetic force. The *true direction* of the resultant magnetic force would be found by suspending the compass needle at its centre of gravity on a universal bearing, such as is described below.

Exp. An *unmagnetized* knitting needle is pushed through the centre of a small cork which is itself supported at the middle by two pins which rest loosely in a zinc stirrup (Fig. 38). The needle is first adjusted in the cork so that it balances in any position, *i.e.* at its C.G. The needle, with stirrup attached, is then carefully placed with its ends resting in two grooved blocks so that it may be *magnetized* without disturbing the adjustment of the stirrup. After magnetization the apparatus is hung by a fine thread from a wooden stand and allowed to come to rest in mid-air. The needle sets itself, under the influence of the Earth's magnetic force, in the magnetic meridian with its N-pole dipping down towards the N. at an angle of 67° (approx.) with the horizontal. This angle is called the **angle of dip** or **inclination**. The position of the needle indicates the direction of the lines of force of the Earth's magnetic field at the point of observation.

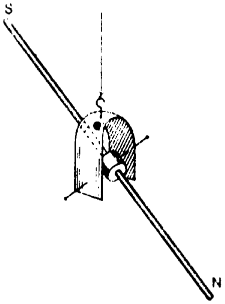


Fig. 38.

26. The Earth a magnet.

The Earth behaves as if it were a huge magnet: its magnetic "north" pole is in the peninsula of Boothia Felix (British North America), its "south" pole is within the Antarctic circle. A model (Fig. 39) may be made by supporting a strongly magnetized steel bar within a hollow wooden sphere, at a position corresponding with the Earth's magnetic axis. Holes must be bored in the sphere at points $N_m S_m$, the magnetic N- and S-poles, which are respectively 17° from the Geographic N-pole and 18° from the Geographic S-pole, the latter being measured on a circle of longitude 110°

(approx.) W. of the circle of longitude passing through the Geographic and Magnetic N-poles.

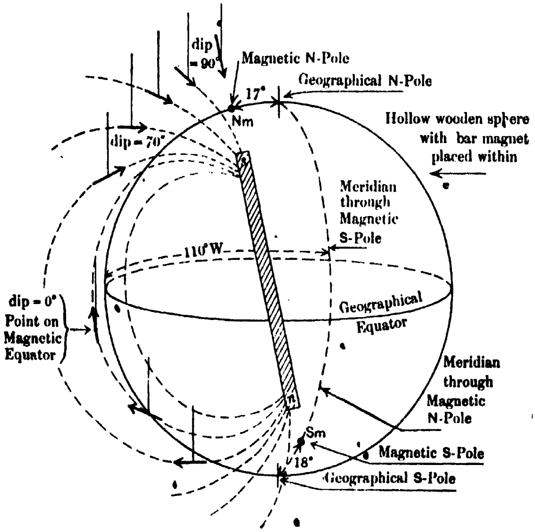

dip = 90°
Magnetic N-Pole
Geographical N-Pole
17°
Nm
Hollow wooden sphere with bar magnet placed within
dip = 70°
Meridian through Magnetic S-Pole
110°W
dip = 0° Point on Magnetic Equator
Geographical Equator
Meridian through Magnetic N-Pole
n
Sm
Magnetic S-Pole
18°
Geographical S-Pole

Fig. 39.

Between these holes the magnetized rod must be fixed with its S-pole towards the Geographic N. If now a small magnetized sewing needle, suspended by a silk fibre attached to its C.G. by soft wax, is moved from the N. magnetic pole towards the South, it will set itself at angles which indicate the direction of the Earth's magnetic force at various latitudes. [See the suspended arrows, Fig. 39.] It is possible in a large model to show alterations in

(*a*) the angle of *dip* or *inclination*, (*b*) the angle of *variation* or *declination* with the Geographic meridian. [See also Figs. 40*a* and *b*.]

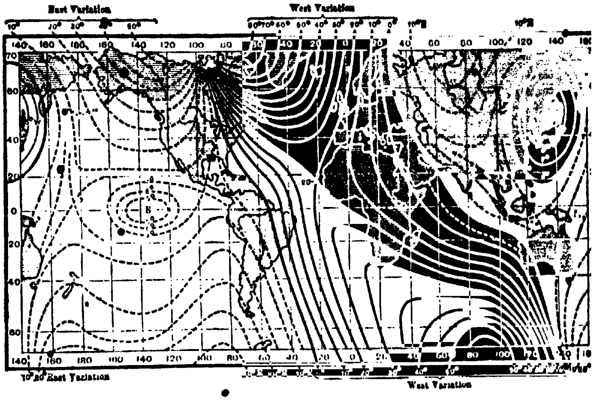


Fig. 40 (*a*). Lines of equal variation (isogonics).

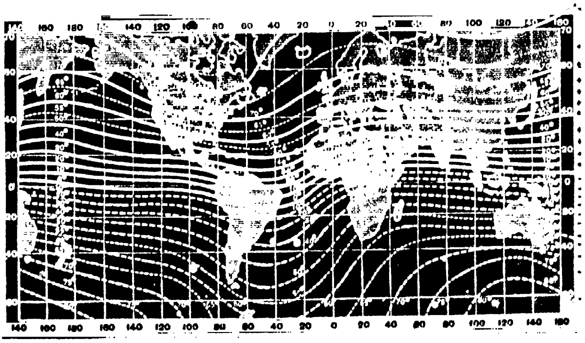


Fig. 40 (*b*). Lines of equal dip (isoclinics).

It will be seen that the angle of dip varies from 90° at the magnetic pole to 0° at the magnetic Equator.

By moving the needle (approximately along lines of latitude) so that the *dip remains constant* we are tracing *isoclinal lines.* Lines along which the *variation* is constant are called *isogonal lines* (of equal declination). The isoclinal along which the dip = 0° is called the *magnetic* Equator.

Exp. Use the small exploring needle described above for finding the *true* direction of the resultant magnetic force in the neighbourhood of one or more magnets placed in various positions.

27. The Dip Circle.

Is an instrument used for measuring the magnetic dip, a simple form of which is shown in Fig. 41. The method of using is as follows: the dip-circle is first placed with its plane in the E. and W. position—the N-pole then points vertically downwards. The instrument is next rotated on its base through an angle of 90°: the plane is now in the magnetic meridian and its horizontal axis

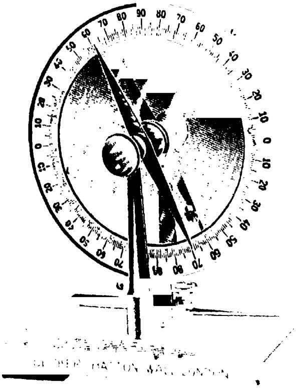


Fig. 41.

points E. and W., the needle is therefore free to take up the position of maximum dip which may be read off. There are however several sources of error.

Source of Error	*Correction*	No. of Readings
(1) The line joining the two points of support may not pass through the centre of the circle.	Take the mean of the readings at each end of the needle.	2
(2) The zero-line may not be level.	Turn the whole instrument on its base through 180° and repeat the two readings above (1).	2
(3) The magnetic axis may not lie on the line joining the two needle points.	Rotate the needle on its bearings and repeat (1) and (2).	4
(4) The line joining the two points of support may not pass through the Centre of Gravity.	Remagnetize the needle so that the poles are reversed and repeat the above eight readings.	8

28. Changes in the angles of Dip and Variation (Declination).

The *directions* of the lines of force in the Earth's magnetic field are subject to (1) daily, (2) annual and (3) prolonged periodic changes, and the *intensity* of the force also varies. Sudden and violent disturbances are known as *magnetic storms* which seem to be closely connected with the appearance of *sun-spots.*

By far the most important change is that of **variation** (declination) which may be accounted for by the theory that the magnetic N. pole moves in a circle of about 20° radius (gyrates) round the Geographic N-pole once in about 1000 years. In the year 1580 the compass at London pointed about 11° E.; by 1660 it pointed due North and in 1820 the variation had reached a maximum of 24° W. This westerly declination is now decreasing being at present about 15° W.

29. Measurement of Magnetic Force.

A glance at the maps of magnetic fields round bar magnets shows that the exact position of the pole is rather indefinite. For investigating the laws of force between two magnetic poles it is usual to employ a magnetized steel rod ending in soft iron balls (Robison's magnet, Fig. 42). A filing map or an exploring compass reveals the fact that the poles of such a magnet are "concentrated" at the centres of the spheres. [Try this.] Good results are however obtained by using long knitting needles and assuming that the poles are situated about $\frac{1}{12}$ the length of the needle from each end.

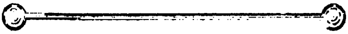


Fig. 42.

Assuming that magnetic force radiates out from a centre we should expect the "inverse square law" to hold good[1]. Let us try

Exp. To show that the force between two magnetic poles varies inversely as the square of the distance between them.

A magnetized knitting needle or a Robison's magnet *Am* is supported vertically in one pan of an accurate balance and counterpoised. Another magnet *Bn* is clamped in the position shown in Fig. 43, like poles being placed adjacent.

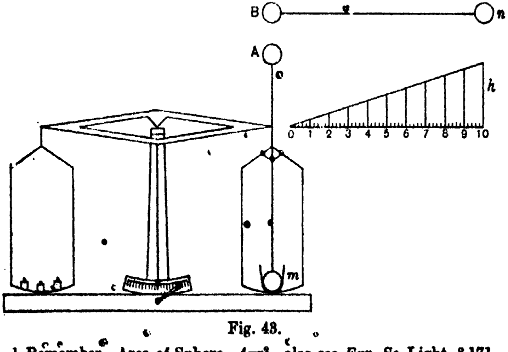


Fig. 43.

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[1] Remember—Area of Sphere $=4\pi r^2$—also see *Exp. Sc.* Light, § 171.

Weights are then added to the left pan to restore equilibrium

$$= W \text{ grams} = \text{Force of } Wg \text{ dynes} = F.$$

The distance **d** between the balls A and B is next accurately measured by inserting a paper wedge whose *base* is divided into 10 equal divisions and whose height (**h**) is accurately measured and made slightly greater than the greatest distance to be measured between A and B. If the wedge first touches each ball at the point 4·7 (say) then $d = 0{\cdot}47h$. Find the radius of each ball by the screw gauge $= r_1$ and r_2, then total distance D between the poles

$$= d + r_1 + r_2 = D.$$

On varying the distance (d) and finding the weight (w) required to restore equilibrium it will be found that

$$F \propto \frac{1}{D^2}.$$

Actual **Observations** taken

Total Distance between Poles D	Weight required (W) to restore equilibrium	If $W \propto \frac{1}{D^2}$, then $WD^2 = k$.
1 cm.	0·280 gram	·28 × 1 = ·28
2 cms.	0·070 ,,	·07 × 4 = ·28
3 cms.	0·030 ,,	·03 × 9 = ·27
4 cms.	0·017 ,,	·017 × 16 = ·27

Hibbert's Magnetic Balance.

That the law of inverse squares applies to magnetic forces may also be proved by the use of Hibbert's Balance (Fig. 44) in which a delicately balanced Robison's magnet is brought under the influence of a second magnet. The *distance* is measured on the upright scale to which the second magnet is fixed, and the *force* is measured by moving a rider of known weight along either arm to distances from the fulcrum marked on a fixed horizontal scale.

30. Unit of Magnetic Force.

If two *like* poles of equal strength, placed *one centimetre* apart, *repel* each other with *a force of one dyne*, each is said to be **a unit magnet pole** or to possess **unit pole strength.**

Thus a N-pole of **m** units repels a unit N-pole at 1 cm. distance with a force of **m dynes** and a N-pole of **m** units repels a N-pole of **m_1 units** with a force of **mm_1 dynes.**

If the **distance** apart of the poles is **d** cms., then the force of repulsion $= F = \frac{mm_1}{d^2}$ dynes.

This equation may be stated as the **Second Law of Magnetic Force:**

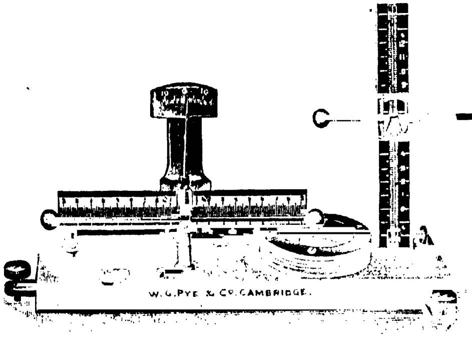

Fig. 44.

If it were possible to isolate two magnetic poles and concentrate them at two points, then **the force** between them would be **proportional to the product of their pole strengths** and **inversely proportional to the square of the distance** between them.

31. Intensity of a Magnetic Field.

Having considered the force which one magnet pole exerts upon another, we proceed to find a method of measuring the **intensity** of a field of force such as the Earth's magnetic field. This is obtained by measuring the **force exerted on a unit magnetic pole** placed in the field. A field is said to have **unit intensity** if the **force exerted on a unit N-pole is one dyne.**

Intensity of the Earth's Field (I).

Let us imagine that it is possible to isolate a unit N-pole U. This unit is pulled with a force of I dynes in the magnetic meridian in the direction of the angle of dip (δ), *i.e.* in England towards the North at an angle of 67° with the horizontal (Fig. 45).

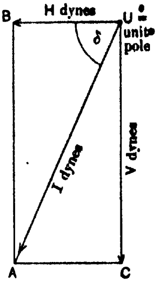

Fig. 45.

Let UA represent, in magnitude and direction, this force of I dynes.

By completing the rectangle $ABUC$, we obtain the horizontal component $UB = H$ dynes and the vertical component $UC = V$ dynes.

Then, since $UC = AU\sin\delta$, $V = I\sin\delta$,

and $UB = AU\cos\delta$, $H = I\cos\delta$.

$$\therefore \frac{V}{H} = \tan\delta,$$

also $I = \sqrt{H^2 + V^2}$.

From the above equations we may find the values of V and I if the values of H and δ are known.

δ, the angle of dip, varies according to locality and is found by observation $= 67°$ approximately at London.

H is found to be approximately 0·185 dyne at London [see § 37], hence

$V =$ the vertical component at London $=$ ·433 dyne,

$I =$ total force or Intensity of Earth's field $=$ ·472 dyne.

32. The magnetic moment of a magnet [denoted by M].

Let a magnetized needle of pole strength m units come to rest in the position NS under the influence of a field of *unit intensity* whose direction is indicated by the arrow at the left-hand corner of Fig. 46.

Let the distance between the poles $NS = l$ cms.

Let the magnet be deflected through an angle θ and let its new position be N_1S_1.

Draw N_1P through N_1 parallel to NS and let fall a perpendicular S_1P from S_1 on to N_1P.

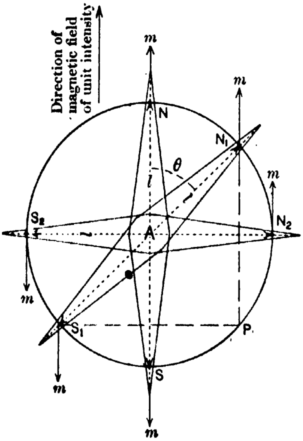

Fig. 46.

Then the needle is acted upon by two equal but opposite parallel forces, at the points N_1S_1, each equal to m dynes, which constitute a couple whose *moment* or *torque* $= m.S_1P$ tending to twist the needle back to the position NS.

The arm (S_1P) of the couple depends on the value of θ, since $S_1P = l \sin\theta$; and the *moment* or *torque*

$$= m.l \sin\theta.$$

The couple reaches its **maximum** when $\theta = 90°$ [position N_2S_2], its moment then $= ml$ denoted by M.

This **maximum moment** or **torque (ml)** of the couple is called the **magnetic moment** of the magnet (**M**).

$$\mathbf{M = ml.}$$

33. Equilibrium of a magnet suspended in the Earth's field (H) and deflected by a force of intensity (F) at right angles to the direction of H.

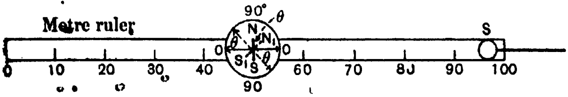

Fig. 47.

The Magnetometer.

To show that in a constant field Deflecting Force is proportional to the Tangent of Angle of Deflection.

[Use the brass compass box (Figs. 26 and 47), with its centre resting on the 50 cm. mark of a metre ruler placed in the E. and W. position.]

Exp. Let Fig. 48 represent the small compass needle NS of the magnetometer (1) *at rest in the magnetic meridian*, each pole being of strength **m** units, and the distance between the poles N and S being $= l$ cms. Then since

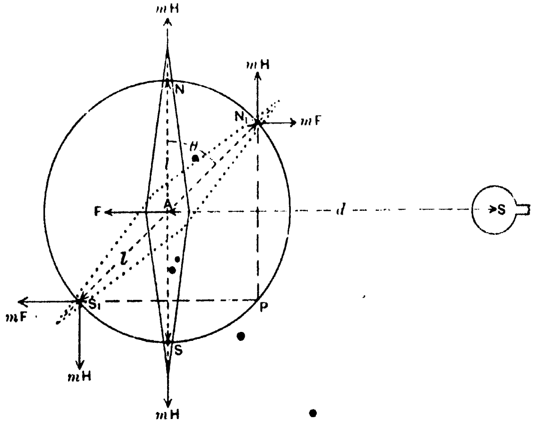

Fig. 48. d = distance between S-pole of deflecting magnet and the axis A of the needle.

H = horizontal component of the Earth's field, each end of the needle will be pulled by a force of **mH** dynes in opposite directions.

(2) Next, let a S pole of a long bar magnet approach from the E-direction, and remain at a distance (d) great compared with the length (l) of the needle producing a field of force of Intensity **F** at A, *i.e.* F units of force on unit pole at the centre of the needle. The needle is deflected through an angle θ to the position N_1S_1 and comes to rest when the deflecting forces mF, mF

due to **S** which have a clockwise torque balance the restoring forces mH, mH which possess a counter-clockwise torque. Since the deflecting magnet pole **S** is at a considerable distance, mF and mF are assumed to be parallel and equal but opposite forces, acting at right angles to the two equal but opposite forces mH, mH. These two sets of equal but opposite parallel forces constitute two balancing couples whose torques may be found as follows. Continue the direction of mH backwards through N_1 to P and the direction of mF backwards through S_1 to P. Then

N_1P is the arm of the couple mF, mF and $mF.N_1P$ is its torque.

and S_1P „ „ mH, mH „ $mH.S_1P$,

$$\therefore mF.N_1P = mH.S_1P \text{ for equilibrium.}$$

$$\therefore \frac{\mathbf{F}}{\mathbf{H}} = \frac{S_1P}{N_1P} = \tan S_1N_1P = \tan\theta,$$

i.e. $\dfrac{\text{Intensity of Deflecting Force } (F)}{\text{Intensity of Earth's Horizontal Component } (H)} = \text{tangent of } \angle \text{ of deflection.}$

This equation expressed in words gives us the **Law of Tangents.**

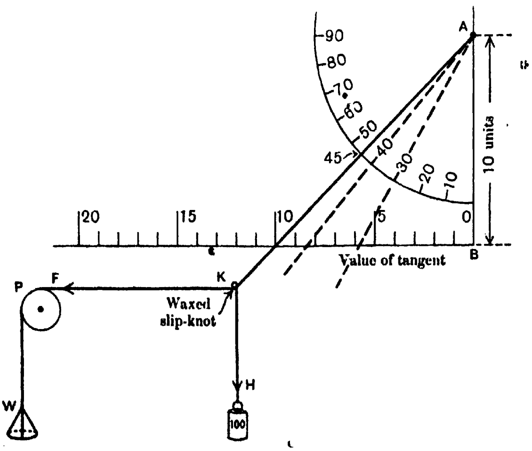

Fig. 49.

34. The Law of Tangents.

If a compass needle is deflected by a magnetic force acting at right angles to the magnetic meridian, the ratio of the intensity of the deflecting field of force to intensity of the horizontal component of the Earth's field is equal to the tangent of the angle of deflection.

Since H is constant for a given place, the *intensity of the field of the deflecting force is proportional to the tangent of the angle of deflection.*

Exp. Illustrate the tangent law as follows. A string $AKPW$ (Fig. 49), tied to a nail A driven into a board, passes over a pulley P (attached to the board) and suspends a weight pan W. At K a second piece of string KH, attached to the first by a waxed[1] slip-knot, supports a constant weight H which corresponds to the Earth's horizontal component. Vary the deflecting force F by adding weights to W and at the same time move the slip-knot along the string so that the direction of F is horizontal; *i.e.* at right angles to KH. Enter your results thus:

Deflecting Force (F) = Wts added + Wt of Pan (12 grams)	Constant Force H = say 100 gms	Angle of deflection = θ	tan θ	$\frac{F}{\tan\theta} = k$
46 + 12 = 58	100	30°	·577	$\frac{58}{\cdot 577} = 100{\cdot}5$
73 + 12 = 85	100	40°	·839	$\frac{85}{\cdot 839} = 101{\cdot}3$
89 + 12 = 101	100	45°	1·000	$\frac{101}{1} = 101{\cdot}0$
108 + 12 = 120	100	50°	1·192	$\frac{120}{1{\cdot}19} = 100{\cdot}9$

The value of the tangent may be read off a horizontal scale drawn (Fig. 49) from a point B vertically below and 10 units from A. Explain this.

---

[1] The wax on the slip-knot prevents the latter slipping along the string when KP is adjusted horizontally.

Exercise. Fig. 50 illustrates a **model**[1] **for demonstrating the Law of Tangents.** The ends of the opposite pairs of strings are joined and support two separate weight pans under the board which is fixed horizontally. Explain the use and mode of working the apparatus.

35. To prove the inverse square law by the magnetometer[2]**.**

A long magnetized knitting needle or, better still, a long Robison's magnet is placed in the position shown in Fig. 51 where the effect of one pole (N) is to a large extent eliminated by placing it vertically above the axis of the needle of the magnetometer, while the other pole (S) is placed at varying distances (d), the corresponding angles[3] of deflection (θ) with their tangents being tabulated.

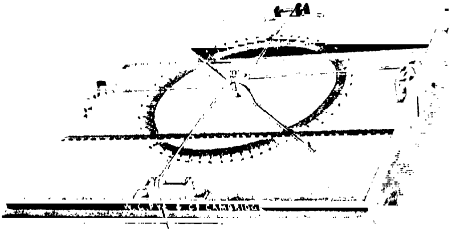

Fig. 50.

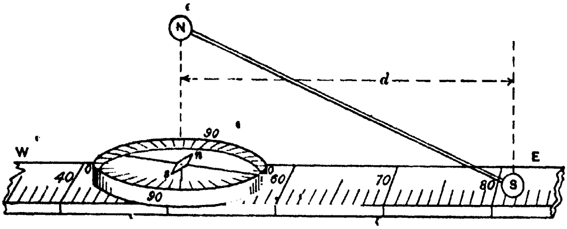

Fig. 51.

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[1] Invented by the Rev. W. Burton of Whitgift Grammar School.

[2] The needle is at first adjusted in the magnetic meridian and the wooden scale in the E. and W. position.

[3] The mean of the readings at ends of the pointer is taken.

Since the deflecting force, F, $\propto \tan\theta$,

it is found that $\tan\theta \propto \frac{1}{d^2}$,

i.e. $d^2 \tan\theta = \text{constant } (k)$.

$$\therefore \mathbf{F} \propto \frac{1}{\mathbf{d}^2}.$$

36. To find the intensity of the deflecting field of force (F) when the influence of **both poles** (strength **m**) of the deflecting magnet and its **length** (l) are taken into account.

I. The magnet placed in the **end-on position.** Place the magnetometer lengthways in the E. and W. position (Fig. 52), the compass needle in the magnetic meridian and the aluminium pointer over 0° of the circular dial. Place a *short* rectangular bar magnet (**ns**) of *length* **l** on the scale with its axis E. and W. [**end-on** position], its centre being **d** cms. distant from the compass needle. Take the mean of the two-pointer readings to obtain the *angle of deflection* ($\boldsymbol{\theta}$). Then

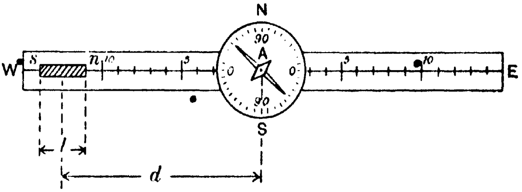


Fig. 52.

distance of n from magnetometer needle $= d - \frac{1}{2}l$,
" s " " $= d + \frac{1}{2}l$.

If we consider the force of each pole (*strength* **m**) of the deflecting magnet on a *unit N-pole* at A, we obtain

$$\text{force } \textit{repelling} \text{ due to } n = \frac{m}{(d - \frac{1}{2}l)^2}$$

$$\text{and force } \textit{attracting} \text{ due to } s = \frac{m}{(d + \frac{1}{2}l)^2}$$

and their difference = resultant force (F) on unit N-pole *repelling*

$$= \frac{2mld}{d^4 - \frac{1}{2}l^2d^2 + (\frac{1}{2}l)^4}$$

$$= \frac{2ml}{d^3} \text{ (approx.) [if } l \text{ is \textit{small} compared with } d],$$

$$\therefore \mathbf{F} = \frac{\mathbf{2M}}{\mathbf{d^3}} \text{ (\textbf{``end-on''} position).}$$

Hence we can find (M) the magnetic moment or torque of the rectangular magnet in terms of H, d and θ.

Since $$F = H \tan\theta = \frac{2M}{d^3},$$

$$\therefore \mathbf{M} = \tfrac{1}{2}.\mathbf{d^3}.\mathbf{H}\tan\boldsymbol{\theta} \text{ ....(1).}$$

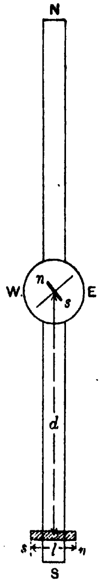


Fig. 53.

* II. The deflecting magnet placed in the **broadside position.** Place the magnetometer *lengthways* in the magnetic meridian and the small deflecting magnet **ns** (pole strength **m**) in the E. and W. position (Fig. 53).

Then, if **l**, **d** and $\boldsymbol{\theta}$ indicate as in I, it may be proved that

$$\mathbf{F} = \frac{ml}{d^3} = \frac{\mathbf{M}}{\mathbf{d^3}} \text{ (\textbf{broadside} position),}$$

hence $$\frac{M}{d^3} = H\tan\theta,$$

$$\therefore \mathbf{M} = \mathbf{d^3}.\mathbf{H}\tan\boldsymbol{\theta} \text{ ....(2).}$$

***37. To find the value of H.** [A "vibration" experiment.] It may be proved that if the small deflecting magnet is suspended and allowed to vibrate about its central geometric axis (Fig. 54), to and fro across the magnetic meridian, the time of vibration being T secs., then

$$T = 2\pi\sqrt{\frac{K}{MH}},$$

[Cf. $t = 2\pi\sqrt{\frac{l}{g}}$; for method see pendulum, *Exp. Sc.* Part I, § 12.]

---

* Omit for first reading.

where **K** is the Moment of Inertia[1] of the Magnet, hence

$$T^2 = \frac{4\pi^2 . K}{M . H} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3).$$

By combining results of Equation (3) with those of either (1) or (2) above the **value of H** is obtained[2].

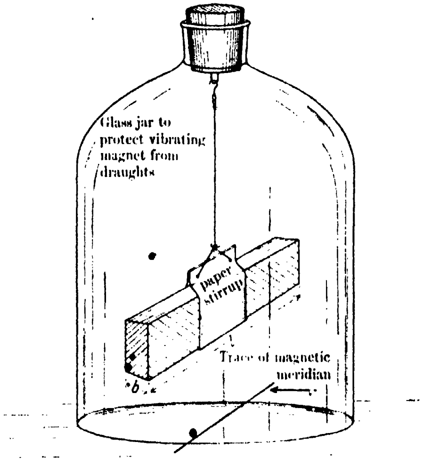

Glass jar to protect vibrating magnet from draughts
paper stirrup
Trace of magnetic meridian
b

Fig. 54.

To find the magnetic moment or torque (M) of the bar magnet.
Insert the value of H obtained in the last experiment in equation (1) or (2).

---

[1] **Note to Teacher.** To facilitate correction of the note-books, it is convenient to use similar *rectangular* bar magnets.

$$K = \frac{\text{mass of magnet in grams } [(\tfrac{1}{2}l)^2 + (\tfrac{1}{2}b)^2]}{3},$$

where l = horizontal length and b = horizontal breadth of magnet.

[2] For another method of finding H see Tangent Galvanometer, § 45.

*38. To compare the Intensities of two magnetic fields H and H_1.

Assuming that the experiment described in § 37 was performed in a part (A) of the laboratory that was free from magnetic forces other than the Earth's field, carry the vibrating magnet to another position (B) where there are known to be large masses of iron, as for instance, heating apparatus, an iron fire place, iron gas pipes or steel gas cylinders. Find the new time of vibration T_1 by averaging the time of (say) 50 complete vibrations.

Then since $$T^2=\frac{4\pi^2 . K}{MH}, \quad T^2=\frac{k}{H},$$

and $$T_1{}^2=\frac{k}{H_1}.$$

$$\therefore \frac{T^2}{T_1{}^2}=\frac{H_1}{H},$$

or if n and n_1 are respectively the number of vibrations in a given time, then

$$\frac{\mathbf{n}_1{}^2}{\mathbf{n}^2}=\frac{\mathbf{H}_1}{\mathbf{H}}.$$

QUESTIONS ON CHAPTER III

1. Two knitting needles, one of which is magnetized, are suspended separately by silk fibres. How would you proceed to discover which is the magnetized needle?

2. Explain the term "magnetic induction." How would you prove experimentally that the attraction between a bar magnet and a piece of soft iron is due to magnetic induction?

3. The N-pole of a weak magnet is found to repel the N-pole of a small compass needle, but when the bar magnet is replaced by a similar one of stronger pole strength, the needle is found to be attracted. Explain this.

4. What is meant by the magnetic axis of a magnet? Describe fully how you would find it in the case of a flat irregular sheet plate. L. M. 1918.

5. What is meant by "variation"? How would you obtain the variation at a given position? A scout is ordered to march by compass from Neuville St Vaast to Thelus on a true bearing of 91° E. of N. If the variation is 13° on what magnetic bearing will he march?

---

* Omit for first reading.

6. An observer, using a compass, sees a tower on a magnetic bearing of 57°. If the variation is 13° what will the true bearing be?

7. How would you make a simple magnetic dip circle if provided with a bar magnet, an unmagnetized piece of sheet steel, thread and any accessories you need?

How would you use the instrument to find the magnetic dip? Explain the cause of the dip and state why a compass needle does not dip.

O. L. J. 1920.

8. What is meant by a magnetic field? Describe how the field due to a bar magnet placed at right angles to the magnetic meridian may be investigated, and give a sketch of the result to be expected. L. M. 1920.

9. What do you understand by "lines of magnetic force"?

Draw the lines of magnetic force between two parallel bar magnets about half an inch apart with (*a*) unlike poles adjacent, (*b*) like poles adjacent.

(Neglect Earth's field.)

10. Given corks, a deep bowl of water, a strong bar magnet, two long knitting needles, devise experiments to illustrate (*a*) the forces of attraction and repulsion between magnetic poles, (*b*) the lines of force between magnetic poles.

11. Define unit magnetic pole, pole strength, field intensity, magnetic moment.

What force does a magnetic pole of strength 5 exert on a similarly charged pole of strength 10 placed at a distance of 7 cms.?

12. Two similar magnetic poles of strength 10 are placed 4 cms. apart. Determine the field intensity at a point (*a*) midway between the poles, (*b*) one cm. away from one of the poles on the line joining them.

13. What is a couple? How is the moment of a couple determined? [§ 32.] What will be the couple exerted on a compass needle of pole strength 3 units, length 3 cms., when it is at right angles to a field of strength (*a*) 10, (*b*) unity?

14. What is a "neutral point" and show how its position in a magnetic field can be determined experimentally?

15. Show that the field intensity due to a small bar magnet at a point on its axis produced is equal to $\frac{2M}{d^3}$, where M is its magnetic moment and d the distance of the centre of the magnet from the point.

16. State and prove the Law of Tangents.

17. Describe and explain a method of verifying the Inverse Square law for magnetic poles. L. M. 1918.

18. What is meant by the statements (*a*) that the strength of a magnetic pole is *m* units, (*b*) that the strength of a magnetic field is *H* units? The distance between the poles of a bar magnet is 15 cms. and the strength of each pole is 100 units. Find the magnitude and direction of the field due to the magnet at a point distant 15 cms. from each pole.

19. Describe the construction of a simple type of magnetometer and explain fully how either (*a*) the magnetic moment of a bar magnet or (*b*) the variation with distance of the field due to a bar magnet at points on the axis produced may be determined by its aid. L. M. 1918.

20. Show how you would magnetize two similar knitting needles each by a different method and discover which is the stronger magnet.

21. A bar magnet with its axis E. and W. deflects the compass needle of a magnetometer, placed on the line of its axis produced, through an angle of 25°. Calculate the pole strength of the magnet from the following data: length of magnet 5 cms., distance of compass needle from centre of magnet 20 cms., $H = \cdot 18$ C. G. S. units.

22. In an experiment with a magnetometer, the axes of two magnets were placed in line pointing E. and W., and the compass needle at a point on the line between them. When the centre of one magnet was 12 cms. and that of the second 36 cms. away from the centre of the needle it was found to be undeflected. Compare the moments of the two magnets.

23. Describe carefully how you would proceed to determine the direction of the resultant force of the Earth's magnetism at a given point.

What do you mean by (*a*) the vertical, (*b*) the horizontal component of the Earth's field, and state how you would determine their values in absolute measure?

CHAPTER IV

THE MAGNETIC EFFECTS OF THE ELECTRIC CURRENT LEADING TO THE MEASUREMENT OF CURRENT AND THE THEORY OF MAGNETISM

39. Electric Bell.

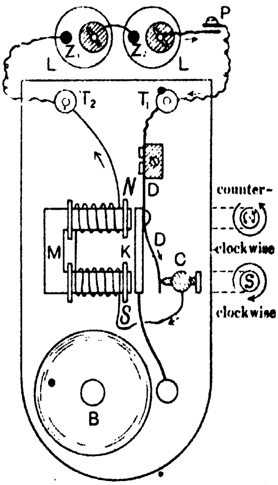


Fig. 55. *L*, Leclanché Cells. *P*, Push. *B*, Bell. *DD*, Spring. *C*, Contact-breaker. *K*, Keeper of Magnet.

The simple magnetic effects of an electric current may be illustrated by experiment with the familiar **electric bell.** Fig. 55 shows a plan of the bell which is connected by wire from its terminals, T_1, T_2, to two Leclanché Cells in series with a "push" contact for completing the circuit. The conventional "direction of the current" is indicated by arrows. The current, entering at T_1, passes along a spring, attached to a soft iron keeper, K, to an adjustable screw C which together with the spring forms the **contact-breaker**; and thence by a wire wound round two bobbins which forms a continuous coil about a piece of iron bent twice at right angles. When the circuit is completed, through the terminal T_2, to the zinc rod (Z_1) of the battery, the soft iron core becomes a magnet, an **electro-magnet,** and attracts the keeper K causing the attached hammer to strike the bell. This attraction breaks the circuit between the spring and screw of the contact-breaker so that the iron core returns to its original unmagnetized condition and the spring flies back, strikes the screw and completes the circuit once more; and so the process is rapidly repeated.

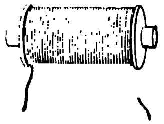
Exp. 1. If a small compass needle is brought near each end of the soft iron core while the bell is ringing, it shows that (*a*) an electro-magnet possesses N- and S-poles corresponding to those of a permanent magnet;

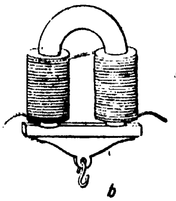
(*b*) magnetization ceases when the current is broken;

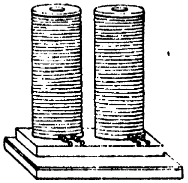
(*c*) the polarity is reversed when the direction of the current at T_1, T_2 is reversed.

Exp. 2. Examine the direction of the current as you look into the face of each pole. (*a*) When the current passes in a **clockwise** direction a **S-pole** is facing you, Ⓢ;

(*b*) if **counter-clockwise**, a **N-pole** is facing you, Ⓝ. (Fig. 55.)







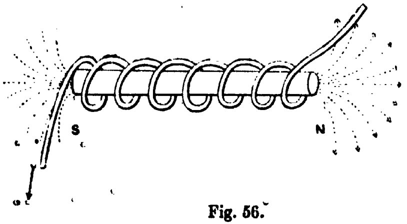


Fig. 56.

Exp. 8. Confirm the relationship between **polarity** and **direction of current** by using *either* electro-magnets as illustrated in Figs. 56 *a*, *b*, *c*; *or* simply by magnetizing a straight soft iron core as in Fig. 56 *d*; *or* a U-shaped soft iron core by the method indicated in Fig. 57.

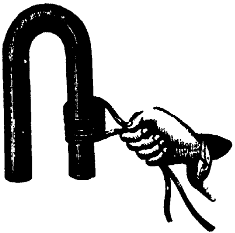


Fig. 57.

Practical Exercises. 1. Make an electric **Buzzer,** by replacing the keeper and hammer with a short steel spring.

2. Alter the adjustments of the contact-breaker in order to convert the trembler electric bell into a **single stroke** gong.

40. The Solenoid and Magnetic Shells.

Exp. 1. Wrap a continuous coil of wire in one direction only, round a hollow cardboard cylinder, and suspend the latter from an adjustable beam

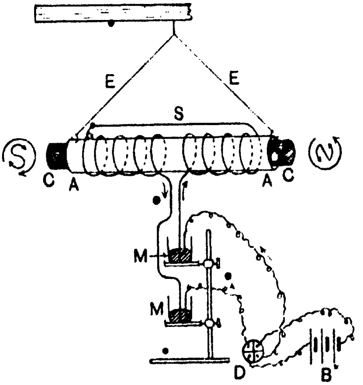


Fig. 58. *AA*, Cardboard Cylinder. *CC*, Removable soft iron core. *S*, Solenoid. *MM*, Porcelain cups of mercury. *EE*, Phosphor bronze suspension. *B*, Battery. *D*, Commutator.

by a wire of phosphor bronze *E* as shown in Fig. 58. The ends of the coil-wire dip into two cups of mercury placed vertically below the point of suspension.

Current from a battery or from the lighting main supply[1] is passed through a commutator [§ 52] to the coil by way of the mercury cups. Such a coil is known as a **solenoid.** When the current is passed the **coil sets** itself **in the N. and S. direction.** Show that (1) it possesses polarity by means of a magnet or compass needle; (2) the polarity is reversed on changing the direction of the current; (3) the magnetic effect is increased on placing a solid core or a bundle of wires of soft iron or steel inside the cardboard cylinder.

Exp. 2. Test the wires, on removal, for permanent magnetization—the *steel* becomes *permanently* magnetized, the *soft iron* only temporarily while inside the solenoid through which current is actually passing.

Exp. 3. De la Rive's Floating Battery. A voltaic cell is made by floating the zinc and copper plates attached to a large cork in a bowl of dilute sulphuric acid (Fig. 59). The wire conveying the current is coiled closely so as to form a circle the plane of which is found to possess the magnetic properties of a thin plate or **magnetic shell,** as it is called, having N- and S-pole faces. Test this with (1) a permanent bar magnet, and also (2) a small compass needle; and try to imagine the directions of the lines of force with regard to this shell. By remembering the direction of the lines of force about a bar magnet (§ 24), it will be found that the floating *coil tends to set itself so as to include the greatest number of lines of magnetic force of an external magnetic field.*

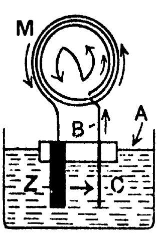


Fig. 59. *A*, Dilute sulphuric acid. *B*, Cork. *M*, Magnetic shell.

Deductions and Recapitulation.

From these experiments we conclude that:

(1) a current-bearing circuit produces a magnetic field of the kind that would be formed if the plane enclosed by the circuit were a thin magnetized plate or shell:

(2) a solenoid is a series of such magnetic shells having the same central axis:

(3) these electro-magnetic coils tend to set themselves so as to include a maximum number of lines of magnetic force of an external magnetic field:

(4) iron is more permeable to these lines than air is [§ 49]:

(5) steel may be magnetized permanently if it is placed in a magnetic field produced by a current of electricity.

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[1] **See Note on Caution next page.**

41. Lines of Force of an electro-magnetic field.

Exp. 1. Make a filing-map of the lines of force of the magnetic field caused by passing an electric current through a circular coil of insulated wire, Fig. 60. The plane of the map is horizontal and contains the axis of the coil. Good results are obtained by passing a current of one or two ampères, preferably from the main supply[1], through a coil of 20 or 30 turns of No. 22 wire with a lamp resistance in the circuit. It is observed that the *lines of force* are

(*a*) uniform at the centre of the coil where their direction is at right angles to its plane;

(*b*) approximately circular and continuous where the coil itself passes through the paper.

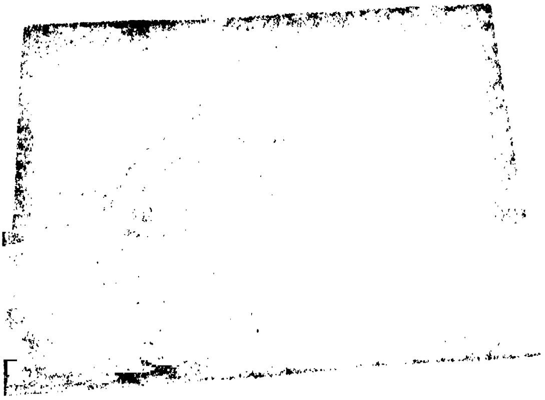

Fig. 60.

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[1] **Caution.** In using the lighting main supply for experimental purposes place a *lamp resistance* [see Appendix I] in the circuit, together with a precaution *fuse*, and **never touch the apparatus when the current is switched on.**

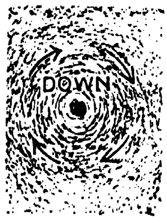

Fig. 61. Lines of magnetic force about a current-bearing wire.

Exp 2. This latter observation (*b*) suggests the presence of *a magnetic field of force round any conductor carrying a current of electricity.*

A current of a few ampères from the main supply (**Caution**) is sent through a lamp resistance in circuit with a vertical wire which passes through a horizontally placed card sprinkled with iron filings. (Fig. 61.) Immediately the current is switched on the presence of a magnetic field around the wire is revealed by the filing-chains following the lines of force which are circles whose centres are in the wire and whose planes are at right angles to it.

Exp. 3. There yet remains **to find the direction of the lines of force** by means of a *small compass needle*, having regard to *the direction of the current.*

Remember that the positive direction of a magnetic line of force is that in which a N-magnetic pole moves when it is placed in the field.

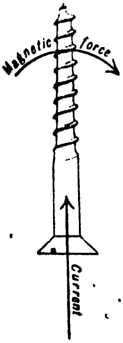

Fig. 62.

The **Screw** or **Corkscrew Rule.** Imagine that you are screwing an ordinary *screw* or a *corkscrew* into a cork held so that the point of the screw travels in the same direction as the current, then *the direction of the rotation of your thumb* and of the screw indicates *the direction of the lines of force.* [Fig. 62 and also refer to Fig. 61.]

Ampère's Rule (1). Imagine yourself *swimming*[1] in the wire *with the current* and facing a suspended magnetic needle: the *N-pole* is deflected *towards your left* hand. Test this by placing a current-

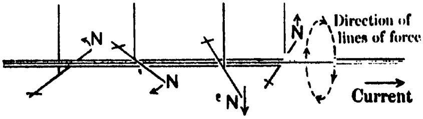

Fig. 63.

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[1] With ordinary breast stroke.

bearing wire alongside of and also both (1) above and (2) below a suspended magnetic needle (Fig. 63).

*41 (*a*). Converse Extension of Ampère's Rule (ii).

We must bear in mind that in the last experiment there are *two* main *fields of magnetic force*: (1) that due to the *current*, (2) that due to the *magnet*, which react mutually. So far the magnet has been free to move and the wire fixed. Now let the *magnet* be *fixed* and the *wire be free* to move *sideways*. By Newton's III Law to every action there is an equal and contrary reaction; therefore the wire will be translated bodily according to the following modification of Ampère's Rule:—*Imagine yourself swimming in the wire, with the current*, and *looking along the lines of force* (in this case [Fig. 64] *away from* the N-pole of the fixed magnet), then the wire will be carried towards your left.

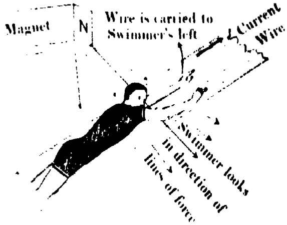
Magnet
N
Wire is carried to Swimmer's left
Current
Wire
Swimmer looks in direction of lines of force

Fig. 64. Motion of Current in Magnetic Field.

[N.B. If the magnet pole were S, the swimmer would have to turn on his back and *face the S-pole* in order to look in the direction of the lines of force.]

*41 (*b*). Further Extension of Ampère's Rule (iii) [Induced Currents].

There yet remains the consideration of a *third* condition, viz. when a wire forming part of a circuit which does *not* contain a battery or other generator of electric current is moved across lines of magnetic force. Here energy to move the wire must be supplied [§ 54].

The result again follows from Newton's III Law. Moving the wire across the lines of force of the magnetic field results in a *production of current* in the wire, and this **induced current** *tends to cause motion* [Ampère, § 41 (*a*)] in a direction **opposing** the movement of the wire caused by the energy supplied. Therefore the *direction* of this induced current is determined by considering the question of *reaction* or opposition to the force used in moving the wire. Hence, when we consider the case of moving a wire so that it cuts across lines of magnetic force and the consequent induction of current in the wire, we must modify Ampère's Rule, thus:—*Imagine that* (1) *you are swimming in a wire* which is *moving across* (cutting) the *lines of force* of a

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* Omit for first reading.

magnetic field, (2) you turn yourself so as to *look along the lines of magnetic force*, and (3) *the wire* (and you in it) *is being moved* to the *right* (Fig. 65), then you are swimming *with the current* induced in the wire; if *the wire is moved to the left*, the current is *against* you[1].

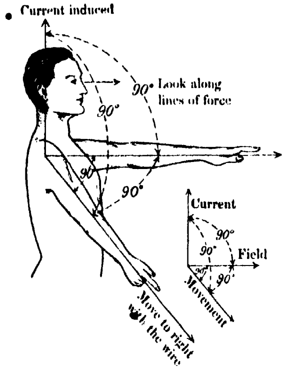

Fig. 65. Current induced by motion of conductor in Magnetic Field.

42. **Galvanoscopes.** (Current Detectors.)

The simplest form of galvanoscope is shown in Fig. 66: it consists of a compass needle surrounded by a coil which carries the current. Deflection of the needle may be explained *either* by the "Corkscrew" and Ampère's Rules *or* by considering the magnetic field produced by the current in the coil as due to a magnetic shell with N. and S. faces, repelling the corresponding poles of the compass needle.

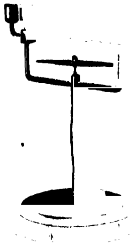

Fig. 66.

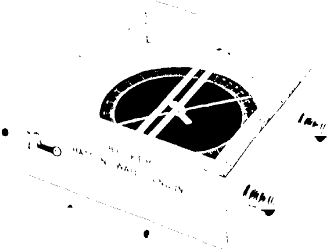

Fig. 67.

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[1] **For Fleming's Right-hand Rule see § 54: it is *best*, however, *for the beginner to master Ampère's Rule, with its extensions, before considering any other rule.***

Fig. 67 shows a slightly more specialized type which the student may easily construct.

Exp. i. To make a galvanoscope (detector) which afterwards [Exp. iv, § 45] may be calibrated as a galvanometer (measurer).

Two strips of wood *AB*, *CD* are glued along the sides of a rectangular piece *ABCD* so as to make a frame in which a magnetometer needle (Fig. 26) and case may be placed. Two wires, the one thick and in two turns of low resistance, the other thin and of many turns of high resistance, are wound round the frame in series as shown in Fig. 68 and attached to the three binding screws $T_1T_2T_3$. The magnetometer needle is placed in the frame under either coil as the experiment requires and its sensitiveness is increased by use of a **control** magnet SN which serves (1) to decrease the strength of the Earth's field or (2) to adjust the pointer to the zero position before current is passed through the coil.

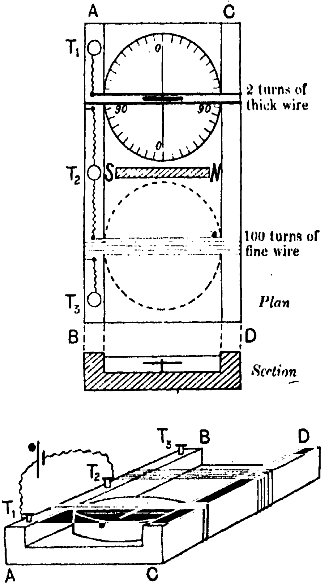


Fig. 68.

Exp. ii. Try the effect of the current from *one* Leclanché cell on the magnetometer needle placed under each coil in turn, when the *control* magnet (*a*) is far removed, (*b*) strengthens the Earth's field, (*c*) diminishes the force of the Earth's field. Draw diagrams of the lines of force to explain all cases and record results.

N.B. Do not "short-circuit" the cell unnecessarily: use a *plug* or "key" *to complete the circuit, remove the plug immediately the readings are obtained* and remember to take the mean of the readings at *each end of the pointer*: avoid *parallax* error.

Exp. iii. Repeat Exp. ii, using two Leclanché cells, (1) in *series*, (2) in *parallel*. Record your results.

Railway Telegraph.

A modified kind of current **detector** (galvanoscope) consisting of two coils wound in the same direction—a *divided solenoid* in fact—may be constructed by the student: the deflection of the magnetized needle, suspended between the two separated coils, is increased by each coil aiding the other. We may view the deflection in the light of Ampère's rule, or from the stand-point of two magnetic shells of opposite poles on either side of the needle. The common **Railway Telegraph** (the old fashioned Post Office pattern) is an instrument of this kind; the needle, weighted and pivoted so as to stand upright when not in use, is deflected to right or left according to the direction of the current which is changed in direction by a *commutator* or by a "three-way" lever shown in Fig. 69 where the two halves of the battery are used separately but in opposite directions as the lever is switched to right or left. Two small gongs [G_1, G_2] of different notes are sounded by the upper part of the needle, the two notes corresponding to the dots and dashes of the Morse code [§ 109].

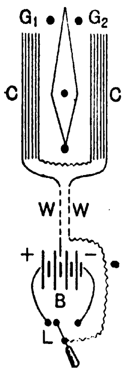


Fig. 69. *CC*, Coil. G_1G_2, Stops. *W'W'*, Line wires. *B*, Battery. *L*, Three-way lever.

43. Control of Sensitiveness.

Besides the method of control mentioned above where a bar magnet was introduced to reduce the force of the Earth's field, an **astatic pair** of needles [§ 22] may be used, round one or both of which the current-bearing coil is placed (Figs. 70 *a* and *b*). Such an instrument is often called an **astatic galvanometer**, although it does not *measure* current.

Torsion and **Spring** control. In some forms of Galvanometers, Ammeter and Voltmeters, the needle is suspended by a wire the *torsion* of which not only serves to control the amount of deflection but also may be used to measure the current if the instrument is calibrated by a standard instrument. In other forms the magnetized needle (or, as we shall see later [§ 47], a suspended coil magnetized by the current itself and so taking the place of the needle) is attached to a *hair-spring* which controls the swing by a method of suspension similar to that of the balance-wheel of a watch.

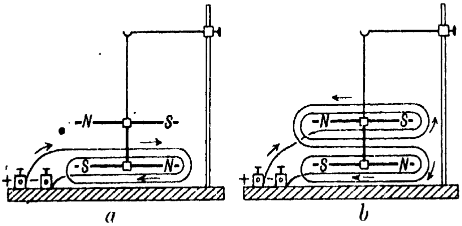


Fig. 70.

44. Mirror Galvanometer.

The angle of deflection of the needle may be more accurately measured by an optical method. In the *Mirror Galvanometer* (Fig. 71) the needle is cemented to the back of a small circular mirror *M* which is suspended by a silk fibre at the centre of the coil *AB*. The angle of deflection θ is measured from the amount of displacement of a beam of light which is reflected from the mirror on to a scale *DWK*. The normal position of needle and mirror is in the plane of the coil and is obtained either by placing the coil in the magnetic meridian or by use of a control magnet. At the centre of the scale *DWK* and at right angles to its length is an adjustable tube holding a lens at *L* and a cross wire at *W*. The scale is placed horizontally and parallel to the plane of the coil and, for purposes of calculation, either 50 or 100 scale divisions from it. The *lens is adjusted* so that the *image of the cross wire* which is fixed vertically across a hole at the centre or zero division of the scale, is reflected back from the mirror and focussed on the

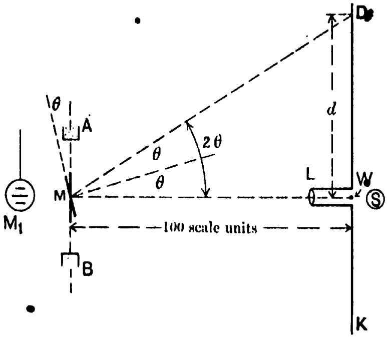


Fig. 71. *AB*, Section of Coil with its plane in the magnetic meridian. *M*, Small mirror with needles attached as at M_1.

scale. In the normal or zero position a beam of light from a source *S* strikes the mirror, *M*, normally and is reflected back along itself.

Let the needles, *i.e.* the mirror, be turned through an angle of θ **radians**, then the reflected beam will move through an angle of 2θ radians[1], and the path of the beam is *WMD*, where *WD* is the *displacement* of the spot.

Measure $WD =$ (say) 36·4 scale divisions.

„ $WM =$ „ 100 „ „

Then $$\frac{WD}{WM} = \tan 2\theta = \frac{36 \cdot 4}{100} = 0 \cdot 364,$$

which corresponds to an angle of ·3491 radian or 20°.

$$\therefore \theta = \cdot 1745 \text{ radian or } 10^\circ.$$

---

[1] See § 188, *Experimental Science*, Part I, Physics, Sect. V, Light.

N.B. It will be found by calculation that, if the *displacement is small*, (say) 20 scale divisions (where $SM = 100$),

$$\tan\theta = \theta \text{ radians (in circular measure)},$$

or, in words, for *small* angles, the tangent of an angle equals the angle measured in radians.

45. Measurement of Current by deflection of a small magnetic needle at the centre of a circular coil placed in the magnetic meridian.

Tangent Galvanometer.

We know that (1) the intensity of the magnetic field of force (F) at the centre of a circular coil carrying a current is perpendicular to the plane of the coil [§ 41].

(2) the force of intensity F deflecting[1] a small suspended magnetometer needle from the plane of the meridian through an angle θ is given by the equation

$$F = H\tan\theta \text{ [§ 33]}.$$

It can be proved mathematically and confirmed by experiment that

(3) $$\mathbf{F} = \frac{2\pi nC}{10r}$$

where
$\mathbf{n}$ = number of turns of coil
$\mathbf{r}$ = radius
C = current in Ampères,

hence (4) $$\frac{2\pi nC}{10r} = H\tan\theta;$$

therefore (5) $$\mathbf{C} = \frac{\mathbf{10 \,.\, H \,.\, r \,.\, \tan\theta}}{\mathbf{2\pi n}} \textbf{ ampères.}$$

Assuming this formula for the present (see Exps. pp. 77–8), let us construct an instrument called a *tangent galvanometer* for measuring electric current in ampères. Fig. 72 shows a vertical board or frame fitted with four circular coils, two on each side, each connected to a pair of terminals. The number of turns and the radii vary.

---

[1] Remember F = the intensity of the field of force and is measured in dynes acting on a unit magnetic pole.

Coil No. 1	2 turns ($n=2$)	radius (r) = 7·5 cms.	thick insulated wire
,, ,, 2	2 turns ($n=2$)	,, = 10 cms.	,, ,, ,,
,, ,, 3	5 turns ($n=5$)	,, = 10 cms.	,, ,, ,,
,, ,, 4	100 turns ($n=100$)	,, = 12·5 cms.	fine ,, ,,

A small shelf carries a magnetometer needle which must be

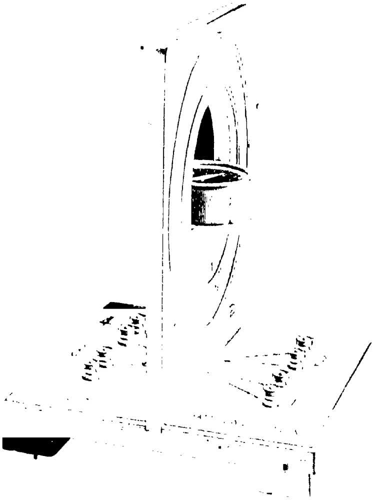


Fig. 72.

adjusted at the centre of the particular coil used, the latter being placed with its plane in the magnetic meridian. A horizontal section of a tangent galvanometer is shown in Fig. 73 which should be compared with Fig. 48.

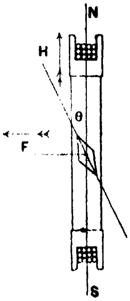


Fig. 73.

Exp. (1). To show that the Intensity of the Field (F) at the centre of the circular coil of a tangent galvanometer (*a*) **varies directly** as the **number of turns n** and (*b*) **inversely** as the **radius (r)**.

Connect the pair of terminals of each coil, mentioned below, of the tangent galvanometer (Fig. 72) in series with one or two Daniell's Cells, having a key or plug in the circuit. Do not complete the circuit until you are ready to take the readings at each end of the magnetometer needle and obtained after tapping the glass gently. Disconnect immediately after this is done. Enter your results as follows:

a. To show that F ∝ n, use coils (2) and (3) which have the *same radius*.

Coil	No. of turns **n**	Readings	Mean deflection θ	tan θ	$F=H \tan\theta$	Ratio $F/n=$
2	**n**=2	13° 15°	14° C.	·249	$F_1=\cdot249\,H$ dynes	$\cdot249H/2=\cdot12$
3	**n**=5	30° 32°	31° C.	·601	$F_2=\cdot601\,H$,,	$\cdot601H/5=\cdot12$

b. To show that $\mathbf{F} \propto \frac{\mathbf{1}}{\mathbf{r}}$, use coils (2) and (1) which have the *same no. of turns*.

Coil	Radius = **r**	Readings	Mean deflection θ	tan θ	$F=H \tan\theta$	$F \times r = k_2$
2	10 cms.	13° 15°	14° C.	·249	$=\cdot249H$ dynes	$2{\cdot}49H$
1	7·5 ,,	18° 20°	19° C.	·344	$=\cdot344H$,,	$2{\cdot}58H$

N.B. More accurate results are obtained by inserting a commutato [see § 52 at the end of this Chapter] between the galvanometer and battery four readings will then be entered in the 3rd column [cf. § 27 (3)].

Exp. (ii). To find the Current (Ampères) in a circuit, use Coil No. 2 and calculate the current by formula (5) above.

$$C = \frac{10Hr}{2\pi n} \cdot \tan\theta.$$

The factor $\frac{\mathbf{10Hr}}{\mathbf{2\pi n}}$ is called the **reduction factor** of the galvanometer. In this case, Coil No. 2,

$r = 10$ cms. and $n = 2$ turns; then, if $H = \cdot 19$ dyne,

the *reduction factor* $= \frac{10 \times \cdot 19 \times 10 \times 7}{2 \times 22 \times 2} = \mathbf{1{\cdot}51}$ approx.

$\therefore$ in Exp. (i) where the current caused a deflection of 14°

$C = 1{\cdot}51 \times \tan 14°$

$= 1{\cdot}51 \times \cdot 249 = \mathbf{0{\cdot}38}$ **Ampère** approx.

Find the current from two Daniell's cells in series or one Bichromate Cell by experiment and formula, using coils (1), (3) and (4) and suggest reasons why the current should be less when Coil No. 4 is used.

***Exp. (iii). To show that the intensity of the field (F) is proportional to the Current.** [Equation (3) above], *i.e.* $F \propto C$, see method of measuring current by rate of deposit of copper by electrolysis, § 61.

Exp. (iv). Calibrate the galvanoscope shown in Fig. 68 so that it may be used as a galvanometer, and prepare a graph deflection current.

46. Electro-magnetic unit of Current.

The problem of investigating the strength of a magnetic field due to a current flowing in a **straight** wire is complicated by the fact that each element of the wire is at a *varying* distance from the unit pole placed at a particular point in the field. Experiment proves that the force *varies inversely* as the *distance* (r) of the point from the wire, *i.e.* $F \propto \frac{1}{r}$.

If however we bend the wire into the form of an arc of a circle and place the unit pole at the centre of the circle then it is found that

$F \propto$ directly as the length of the arc (l),

$\propto$ directly as the current (c),

$\propto$ inversely as the square of the radius,

i.e. $F \propto \frac{l \cdot c}{r^2}$,

and we can choose the *unit of current* (c) so that $F = \frac{lc}{r^2}$.

---

* Omit for first reading.

This unit is called the **electro-magnetic unit of current,** and may be defined in C.G.S. units as the current which *flowing in a wire* 1 *cm. length bent into the arc of a circle of* 1 *cm. radius exerts a force of* 1 *dyne on a unit magnetic pole placed at the centre of the circle*—*i.e.* the current produces a field of unit intensity at the centre.

Current expressed in "E.M." or absolute C.G.S. units is indicated in this book by a small **c**. This unit is too large for practical purposes:

the **practical unit**—the **ampère** = $\frac{1}{10}$ **"E.M." unit.**

Ampères are expressed by a large **C.**

The force (**F** dynes) on unit pole placed at the centre of the circular coil of a tangent galvanometer, of *radius* **r** and **n** turns, is obtained thus:

$$F = \frac{l \cdot c}{r^2} \text{ dynes, where } c \text{ is in "E.M." or absolute units}$$

$$= \frac{2\pi r n \cdot c}{r^2} \quad ,,$$

$$= \frac{2\pi n \cdot c}{r} \quad ,, \text{ [see note below]}$$

$$= \frac{2\pi n C}{10r} \quad ,, \text{ where } C \text{ is in } ampères. \text{ [See also § 79.]}$$

47. Ammeters or Ampère-meters.

By means of a tangent galvanometer connected in series with any other instrument for measuring current we can now tabulate scale readings on the latter corresponding to ampères measured by the galvanometer: this process is called **calibration.** From these observations we can construct a *graph*

ampères/scale readings. [Cf. § 45, Exp. (iv).]

Current measuring instruments are called **ampère-meters** (ammeters) and are chiefly of *three* types—(1) "*moving-magnet,*" (2) "*moving-coil,*" (3) "*moving-iron.*"

Note. Force per unit length of coil $\propto \frac{1}{r^2}$.

Total force at centre of circular coil $\propto \frac{2\pi r}{r^2} \propto \frac{1}{r}$.

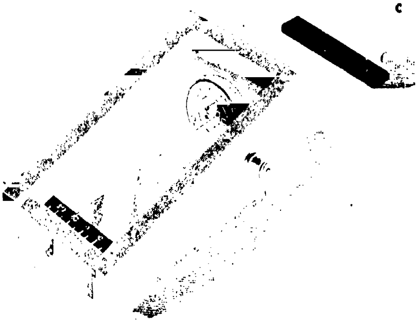


Fig. 74*a*.

(1) A **moving-magnet ammeter** is shown in Fig. 74 *a* where, suspended inside the current-bearing coil, a permanent magnet with pointer attached is deflected by the magnetic field created by the current. This is clearly a *modification of the tangent galvanometer*. A control-magnet for neutralizing the Earth's field increases the sensitivity.

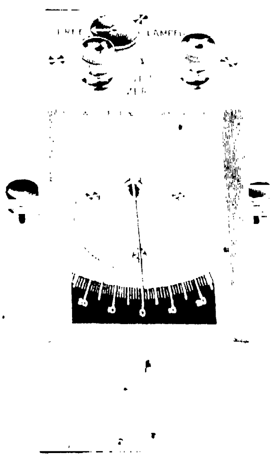
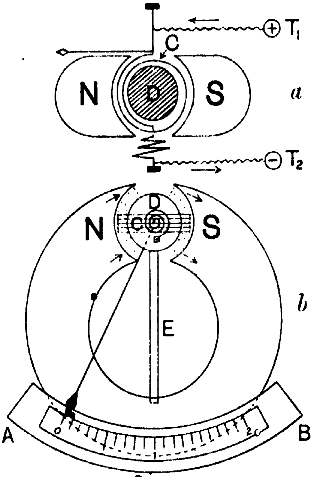


Fig. 74*b*.

(2) A **moving-coil ammeter** is shown in Fig. 74 *b* and the type is explained by Figs. 75 *a* and *b*. The *current*, or rather a small but *known fraction* [see § 71, Shunts], to be measured enters at the terminal T_1 and passes down a wire of phosphor bronze which suspends the coil and thence through a control hair-spring [§ 43] to the

terminal T_2. The plane of the moving-coil is set, for the zero position of the pointer[1], in the plane of the field between the poles of a strong permanent magnet NS, concentrated by an iron core within but not touching the coil. When the current flows, the



Figs. 75 *a* and *b*. *NS*, Permanent Magnet. *C*, Suspended coil carrying current. *AB*, Scale, reading ampères. *D*, Soft iron core. *E*, Brass support.

coil moves across the lines of magnetic force due to the permanent magnet [§ 41 (*a*)] being acted on by a couple which opposes the torsion of the hair-spring and phosphor bronze suspension. When equilibrium is established, it is found that the *deflection is proportional to the current*.

Exp. The principle of the moving-coil galvanometer may be shown by passing a current from two Bichromate Cells through a small coil of fine

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[1] In the most sensitive micro-ammeters the deflection is measured by means of a mirror attached to the phosphor bronze suspension. [§ 44.]

(No. 36) insulated Copper wire of about 200 turns suspended by one of its terminal wires round which the other is wrapped loosely. The coil is hung with its plane in the direct field between the N- and S-poles of a permanent magnet. (Fig. 76.)

(3) **Moving-iron ammeter.** The main feature of this type is a hollow coil of thick wire carrying the current which, by creating a strong magnetic field, magnetizes a moving piece of soft iron within the core. In Fig. 77 a soft iron lever, to which a pointer with compensating weight or spring is attached, is sucked in towards the centre of the core. A section of another kind of moving-iron ammeter is shown in Fig. 78. The *moving-iron* rod *A*, fixed in a frame and pivoted on a spindle shown in section at *O*, is magnetized and repelled by a similar but *fixed* iron rod *B*.

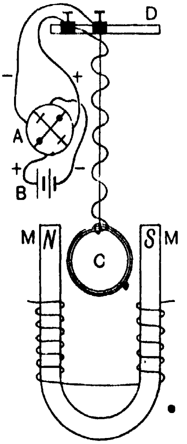

Fig. 76. *A*, Commutator. *B*, Battery. *C*, Coil of 200 turns. *D*, Support. *MM*, Permanent magnet, strengthened if necessary by supplementary current.

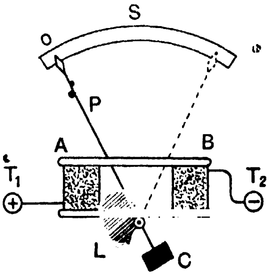

Fig. 77. *AB*, Coil. *C*, Counterpoise. *L*, Soft iron lever. *P*, Pointer. *S*, Scale.

*48. Fields of Force, Lines of Force and Magnetic Flux.

We have already defined a field of *unit intensity* [§ 31]: a unit magnetic pole placed in such a field is moved in the direction of the lines of force with a force of one dyne. We may imagine a sheet of paper to be placed perpendicular to the direction of the lines of force (Fig. 79) and divided into square centimetres which have unit poles at their centres. If the field is of unit intensity we can describe the total force acting across 1 sq. cm. as 1 line of force per sq. cm.: in a field of intensity (say) 7, each of the unit poles would be acted on by a force of 7 dynes, or we could say that there were 7 *lines of force per sq. cm.* If the total area were (say) 10 sq. cms. then there would be 10 × 7 lines of force across the whole area or, to use a new phrase, the total **magnetic flux** would be 70 dynes per total area.

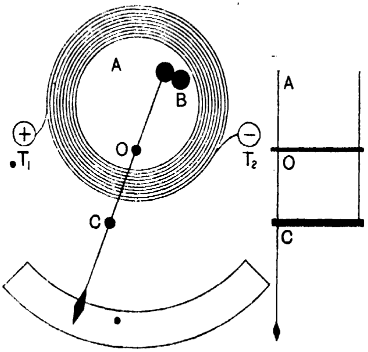

Fig. 78. Section of coil and iron rods. The arrangement of the compensating rod, *C*, is shown on the right.

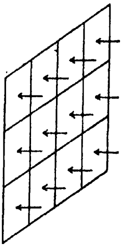

Fig. 79.

In the case of a *unit pole* placed at the *centre of a sphere* of unit radius (1 cm.), the total flux across the surface of the sphere is found by considering the force on a unit pole at the centre of each sq. cm. of the surface at a distance of 1 cm. from the unit pole placed at the centre of the sphere. The force on the unit pole at the surface of the sphere is one dyne. Therefore, since surface of sphere $= 4\pi r^2$, and $r = 1$ cm., the *total flux* is **4π dynes**; if the strength of pole at centre $= m$ units the **total flux** would be **$4\pi m$ dynes.**

---

* Omit for first reading.

49. Permeability.

One of the most interesting facts observed in this chapter is the *increase of intensity* of the magnetic field caused by the *insertion of an iron core* into a solenoid or other current-bearing coil [§ 40].

We can compare the intensities of magnetic fields by a magnetometer, remembering that

$$F \propto \tan\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots [\S\ 33].$$

Suppose that the intensity is found to be (say) 5 lines of force per sq. cm. before the iron is inserted in the coil, and (say) 10,000 after insertion; it is evident that iron is more permeable to lines of force than air is in the proportion of $\frac{10000}{5}$, *i.e.* 2000 times more permeable, or, in other words, the *permeability* of iron is 2000 times greater than that of air, when the intensity of the field of magnetization is 5.

This ratio $\dfrac{\text{intensity of field after insertion of } \textit{iron}}{\text{original intensity of magnetizing field}}$
measures the *permeability* of the iron.

If the magnetizing field is of intensity **H** lines per sq. cm. in air,
and after insertion of the iron there are **B** „ „ iron, steel, etc.
and the Permeability is represented by μ,

then $$\frac{\mathbf{B}}{\mathbf{H}} = \mu.$$

For Exps. see § 50.

50. Magnetization—Magnetizing Force—Hysteresis.

Exp. (1). To prove that the intensity of the field due to a current passing through a solenoid is proportional to the strength of the current.

A solenoid (*S*, Fig. 80), made by winding No. 28 insulated copper wire closely round a glass tube[1] [$\frac{1}{4}'' \times 1'$], is connected in series with a 4-volt accumulator or two bichromate cells (*B*), a carbon-copper-sulphate resistance (R) [§ 69], a commutator (C), and a tangent galvanometer (G). A magnetometer (M) is used to measure the intensity of the field. Then it will be found

---

[1] Secure the ends of the wire by india-rubber rings wound on both the glass and the wire.

$$\frac{\text{Intensity of Field}}{\text{Strength of Current}} = \frac{\tan \angle \text{ of deflection of Magnetometer}}{\tan \angle \text{ of deflection of Galvanometer}} = \text{a constant.}$$

Take 3 or 4 sets of observations, varying the resistance for each set. The mean of four deflection readings must be taken for each instrument—two at each end of the pointer and these repeated after the current is reversed.

Tabulate your observations and show that the above ratio is constant; also draw a graph, plotting the corresponding values of the two sets of tangents[1].

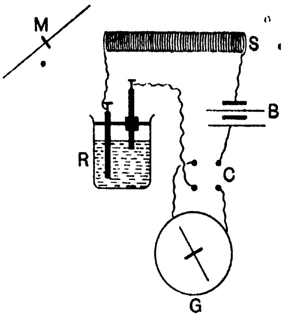

Fig. 80.

Exp. (ii). To prove that the intensity of the field due to a current passing through a solenoid is proportional to the number of turns of the coil per unit of length along the solenoid.

Prepare a second solenoid of exactly the same dimensions as the first [Exp. (i)] but use No. 28 wire. Replace the galvanometer with this second solenoid. Count the number of turns in each and divide by the corresponding length of each solenoid. Take deflection readings of the magnetometer, without altering the total resistance of the circuit, for each solenoid in turn in the *exact* position (S) shown in Fig. 80. Enter your results as follows:

Length of solenoid No. 1, 11 cms. No. 2, 11 cms.

Solenoid Wire	Turns (n) per cm.	Deflections θ		Mean θ	tan θ	Ratio $\frac{\tan\theta}{n}$
		E.	W.			
1. No. 22	20	12·5 12	13·5 14	13°	·231	·0185
2. No. 28	41	23·5 24	26·5 26	25°	·466	·0186

---

[1] **In all these experiments care should be taken to place the solenoids as far as possible away from the magnetometer or galvanometer which it is not intended to affect.**

Having shown that the magnetic intensity of a field is proportional to the current, we may use the same method for showing the *degree of magnetization induced in a piece of iron* in relation to the *magnetizing force produced by a current.* We shall obtain a measure of the former by the magnetometer and of the latter by the tangent galvanometer. By placing a soft iron core within the solenoid [Exp. (i)] and by gradually increasing the current from zero to a suitable maximum, *then* diminishing the current gradually until it becomes zero, *afterwards* **reversing** it until a corresponding maximum is attained but with the current flowing in an opposite direction, and *finally* on diminishing the current to zero and ultimately increasing it to its first maximum, a series of two sets of observations will be taken from which we can plot a curve corresponding to Fig. 81.

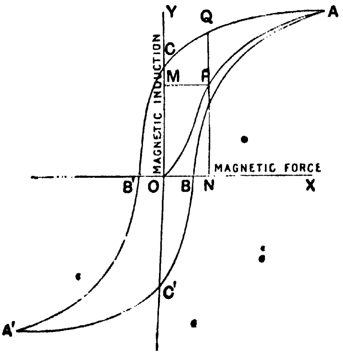

Fig. 81.

Exp. (iii). To investigate the magnetization (magnetic induction) of iron and its relation to the current producing the magnetizing force.

An unmagnetized[1] rod or a bundle of wires made of soft iron about 40 cms.

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[1] Demagnetize the iron if necessary by (*a*) hammering or (*b*) passing suitable current through wire wrapped round one end: test with compass needle.

long is placed in a long solenoid the end of which is placed about 20 cms. from the magnetometer needle (Fig. 80). The coil is connected in series with a tangent galvanometer or ammeter through a commutator to the source of current[1] a suitable resistance being placed in the circuit [see Exp. (i)]. Pass a small current and note the readings of the tangent galvanometer and magnetometer. Increase the current gradually taking readings until a maximum is reached (*OPA*, Fig. 81). Then decrease the current gradually to zero (*AQC*, Fig. 81). Next reverse the current by the commutator and increase the current gradually, taking readings as before, to a maximum (*CB'A'*) and continue until the cycle is complete (*A'C'BA*). Tabulate your results as follows:

Reading	TANGENT GALVANOMETER Magnetizing Force ∝ current ∝ tan δ		MAGNETOMETER Magnetic Induction ∝ tan θ		Corresponding position on Curve, Fig. 81
	δ	tan δ	θ	tan θ	
1	0°	0	0°	0	*O*
2	36°	·727	13°	·231	
3	54·5°	1·4	24°	·445	*P*
4	62°	1·88	28·5°	·543	
5	73°	3·27	35°	·700	*A*
6	62°	1·88	33°	·649	
7	54·5°	1·4	32°	·625	*Q*
8	36°	·727	29°	·554	
9	0°	0	21°	·384	*C*
10	32°	·625	0°	0	*B'*
11	49°	1·15	19°	·344	
12	58°	1·6	28°	·532	
13	62°	1·88	30·5°	·585	
14	73°	3·27	35°	·700	*A'*
15	51°	1·24	31°	·601	
16	31°	·601	19°	·344	
17	0°	0	16·5°	·296	*C'*
18	15°	·267	0°	0	*B*
19	34°	·675	8°	·141	
20	53°	1·33	24°	·445	
21	65°	2·15	31°	·601	
22	73°	3·27	35°	·700	*A*

Plot the curve corresponding to these observations.

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[1] If the main supply is used with an ammeter in circuit a lamp resistance [§ 69] is suitable.

It will be seen from readings Nos. 1–5 that the magnetizing force has been increasing to a maximum, with the maximum of magnetic induction. At A the curve becomes almost horizontal showing that the iron is nearly *saturated magnetically*. Readings Nos. 5 to 9 show a lessening of the magnetizing force until at No. 9 it becomes zero, nevertheless the magnetic induction **lags behind** and is shown by a deflection of 21° of the magnetometer. Reading No. 10 shows that the *reversed* magnetizing force has increased, but the rod has only just become demagnetized—again a lagging behind of the magnetic induction. The student should note the readings Nos. 14, 17, 18 and 22, especially the corresponding but reversed points A' and A, the completion of the cycle, and also the lagging at C' and B. The Greek word ὑστέρησις means a **lagging behind**, hence this curve is called a **hysteresis** curve.

51. Theory of Magnetism.

A magnetic field always exists where electrons are in motion, but not where electrons are at rest: it has therefore been suggested that in the atoms of iron, nickel and other magnetic substances, electrons are revolving or moving in orbits. It is supposed that electrons by their motion produce stresses and strains in the surrounding ether which constitute a magnetic field. On this hypothesis, each atom of (say) iron is itself a magnet possessing a N- and S-pole; when a piece of iron is placed in a magnetic field, these atomic magnets align themselves with opposite poles more or less facing each other until ultimately, as the magnetizing force increases, magnetic saturation occurs.

When the magnetizing force is removed, *soft iron*, in which the atomic structure is supposed to be elastic, relapses into its former condition of indefinite arrangement of the atoms, but *steel* being more rigid retains its magnetism, until it is heated to bright redness, when the atomic structure is loosened under the vibration produced at the high temperature.

Exp. (i). Cut a fine steel wire, previously magnetized, into small pieces. It will be found that each fragment however small still possesses N- and S-poles.

Exp. (ii). A test-tube filled with steel filings is corked and placed in the magnetic field of a solenoid; on removing the magnetizing force the tube is still found to be magnetic; if however the filings are tipped out of the tube, shaken and replaced, the tube no longer exhibits magnetic properties, although we must assume that each particle of steel is still a magnet.

Exp. (iii). Try whether a previously magnetized steel pen retains its magnetism after it has been strongly heated in the blow-pipe flame.

52. Commutators are used for reversing the direction of the current without disturbing connection with the supply of electricity.

(i) The "*plug*" commutator shown in Fig. 15 is the simplest type. Explain by a diagram how it should connect a battery with a galvanometer so that the current in the latter is reversed.

(ii) The "*square*" commutator shown in Fig. 82 possesses four holes, sunk into an ebonite base and filled with mercury, at the corners of a square *ABCD*. Each hole is connected to a terminal screw: adjacent screws may be joined by inserting the insulated pairs of bent wires shown (dotted) in the ebonite slab on the right of the figure.

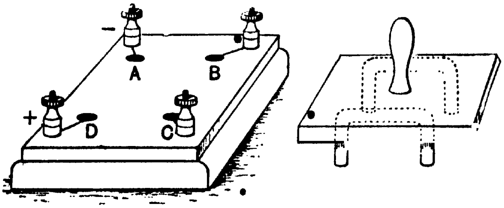

Fig. 82.

(iii) *Ruhmkorff's* Commutator (Fig. 83) is fitted with four terminals, one at each corner of an ebonite base: adjacent pairs are connected in turn by rotating the handle through 180°.

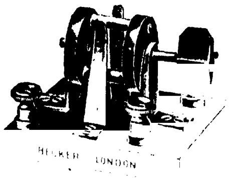

Fig. 83.

(iv) A "*tapping*" commutator of a simple type, which also may be used for signalling in the Morse code either on the direct or on the reversing-current system [§ 42], is shown in Fig. 84. The student should construct one of these commutators and also try to design other forms.

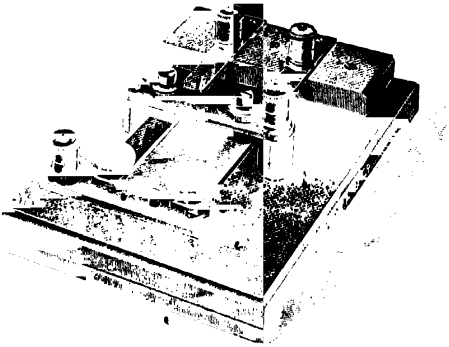

Fig. 84.

The top two terminals are connected to the instrument, the lower two to the battery or line circuit. The tapping levers rest in contact with the middle bar, but this contact is broken by depressing either lever which is then connected to the lower bar with its terminal on the left-hand side.

QUESTIONS ON CHAPTER IV

1. Describe experiments to illustrate the magnetic effects due to (*a*) a straight current, (*b*) a circular current, (*c*) a current passing through a solenoid.

2. State a rule for finding the direction in which a single magnetic pole would move round a wire carrying a current.

A current is flowing along a wire between the two unmarked poles of a storage battery. What method would you adopt to find (*a*) the direction of the current, (*b*) the positive pole of the battery?

3. Two currents, in parallel wires, pass through the points A and B in a downward direction perpendicular to the plane of the paper. Draw a careful sketch showing the direction of the lines of force due to each current and state what conclusions you would form regarding the action of the currents upon each other.

4. Equal currents flow along two straight insulated wires in the same plane, and crossing at right angles at the point O. Determine the direction of the magnetic force at four points A, B, C, D equidistant from O and each on a bisector of the angles between the wires.

5. What do you understand by the term "magnetic shell"?

Draw a careful sketch of a flat coil of wire carrying a current showing (*a*) the position of the magnetic poles produced by the current, (*b*) the direction in which the coil would tend to move if freely suspended in the Earth's field.

6. You are given a cigar box, a small compass needle and some insulated wire. Carefully describe how you would proceed to make a simple form of current detector. What further steps would you take to render your instrument suitable as a direct measurer of current?

7. Make a sketch of a Tangent Galvanometer and briefly describe its structure.

(*a*) Why is it necessary for the coil to be in the plane of the magnetic meridian?

(*b*) If the coil, when carrying a current, is considered as a magnet, what is the direction of the magnetic axis?

(*c*) Why can a permanent deflection of 90° never be obtained?

(*d*) What is meant by the Reduction Factor of the Galvanometer and on what features of the instrument does it depend? O. L. J. 1920.

8. A Tangent Galvanometer is set up with the aluminium pointer in the plane of the coil. No deflection is observed when a current is passed through the instrument. Why is this?

9. How would you experimentally determine the Reduction Factor of a given Tangent Galvanometer?

Two batteries respectively give deflections of 10° and 20° when currents from them are passed separately through a given Tangent Galvanometer. What deflections will be recorded if the current from each battery is doubled?

10. What are the currents in ampères from two cells which respectively give deflections of 13°, 26° in a Tangent Galvanometer of 5 turns, radius of coil 10 cms., $H = \cdot 18$?

11. Define (*a*) the electro-magnetic unit of current, (*b*) the practical unit of current.

The galvanometer in Q. 10 is fitted with coils of 5 turns and 50 turns respectively. It is used for currents which give deflections between 3° and 60°. Determine the greatest and least currents it will measure. Give their strengths in (*a*) E.M. units, (*b*) ampères.

12. A current, passing through a Tangent Galvanometer, gives a deflection of 5° when a single turn coil is used. What deflection will be recorded when the current flows through a coil containing 50 turns?

13. A light flexible cable, of insulated wire, connected to the mains, carries a current whose direction and strength are required. How would you proceed to determine these values without stopping the current or scraping the wire?

14. Describe with careful sketch an Astatic Galvanometer and explain its great sensitiveness as a detector of current.

15. Give a detailed description of (*a*) a mirror galvanometer, (*b*) a **sensitive** moving-coil galvanometer. Which would you prefer to use and why?

16. What is meant by the **sensitiveness** of a galvanometer? How is the sensitiveness varied by the use of a controlling magnet?

17. Define "intensity of magnetization," "permeability."

Describe an experiment to determine how the intensity of magnetization in iron varies with the magnetizing force.

18. What do you understand by the term "hysteresis"?

Draw typical hysteresis curves for (*a*) soft iron, (*b*) steel, stating the facts which may be deduced from the study of the curves.

19. Draw a careful sketch of a simple form of commutator, explaining its use.

CHAPTER V

INDUCED CURRENT

53. Motion of a current-bearing wire in a magnetic field.

The student should refer to § 41 (*a*) and recall the converse of Ampère's Rule whereby the direction of motion of a current-bearing wire free to move in a magnetic field of force may be remembered. A few experiments illustrate this rule.

Exp. (1). A strongly magnetized bar *NS* (Fig. 85) is fixed in a cork which fits tightly into a small copper vessel[1]. Mercury is poured into the vessel and partially supports a thick piece of wire which is hung by a thin copper wire from a wooden stand. The wire and the vessel are connected to the poles of a battery of 8 Bichromate Cells, so that the current passes up the wire which will now rotate round the magnet in a counter-clockwise direction. Imagine

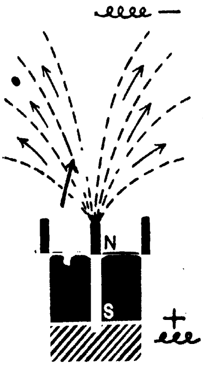

Fig. 85.

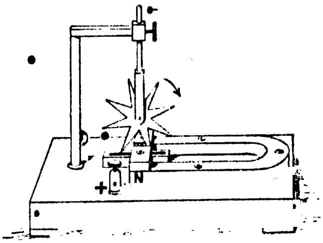

Fig. 86.

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[1] A copper calorimeter serves the purpose.

yourself swimming with the current up the wire with your back to the magnet looking in the direction of the lines of force: the wire is continually urged to your left. Reverse the direction of the current and note that the wire moves round in the opposite direction.

Exp. (ii). Barlow's Wheel. An eight rayed star (Fig. 86) cut out of metal is supported on a horizontal axis so that it can rotate with the ends of the rays just dipping into a mercury trough placed between the poles of a strong horse-shoe magnet. If current is now passed from the terminal + which is connected to the mercury by a wire the wheel rotates in a counter-clockwise direction if the near pole of the magnet is a N-pole.

***Exp. (iii). Electric-motors.** [See also § 100.] In Fig. 87 a coil of wire free to rotate about a horizontal axis and between the poles of a fixed magnet is shown, and arrows indicate the direction in which a current is passed through the coil. According to the converse of Ampère's Rule referred to in Exp. (i), the coil will rotate until it is at right angles to the plane of the paper: by its momentum however it will rotate past this angle and will be brought back to rest after rotating 90° unless the current in the coil is reversed every half revolution. This reversal of the current in the coil is effected by the "split-ring" commutator shown on the right of Fig. 87 and described fully in § 95. The field magnets are wound in series with the coil and therefore actuated by the current passed into the motor. Fig. 88 is a diagram of the lines of force round a conductor in a magnetic field. It shows the lines of force crowded together above the section of the wire and separating: this connotes *repulsion* (Fig. 35). The + sign indicates that the current is passing down the wire through the paper, hence the wire is urged in the direction of the lower arrow. [Converse of Ampère's Rule, § 41 (*a*).]

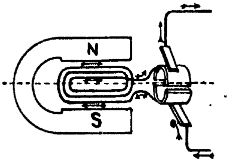

Fig. 87.

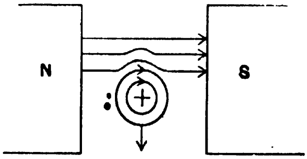

Fig. 88.

The consideration of the lines of force around a current-bearing wire in a magnetic field and the consequent moving of the wire, brings us by a natural sequence to the question of the forces between two conductors placed alongside of each other. Each possesses a magnetic field.

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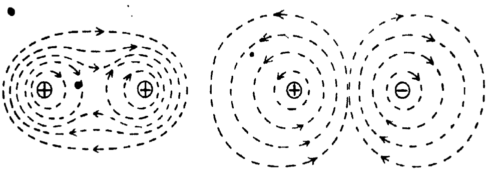
* Omit until after reading § 95, the Dynamo.

(i) If the current is in the **same direction** in **two parallel conductors** the lines of force run into each other (Fig. 89 *a*) and consequently there is **attraction** (Fig. 34).



attraction (*a*) Fig. 89. repulsion (*b*)

(ii) But if the current in the two parallel conductors runs in **opposite directions,** the lines of force avoid each other (Fig. 35) indicating stresses in the ether which cause **repulsion** (Fig. 89 *b*).

Another method of regarding the force (i) of *attraction* (F_A) between *two parallel currents* in the *same direction* and (ii) of *repulsion* (F_R) if in *opposite directions* is to apply the converse of Ampère's Rule in the light of Fig. 90. *A*, *B* and *C* are parallel current-bearing wires: the lines of force are shown for *A* which is considered fixed; the reactions between the wires are however mutual.

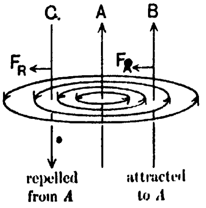


Fig. 90.

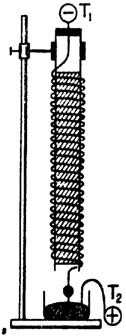


Fig. 91.

Exp. (iv). Roget's Jumping Spiral. A spiral of *insulated* wire is wound loosely round an iron rod which is clamped into a stand as shown in Fig. 91. The spiral is fixed to a supporting terminal T_1 at the top; the lower end, which is weighted, ends in a piece of platinum wire which just touches a cup of mercury connected to the terminal T_2. On passing a strong current through the spiral the parallel wires are *attracted* and the current is broken at the mercury, but contact is renewed immediately, by gravity, and the spiral contracts again.

54. Induced Current. Conductor cutting magnetic lines of Force.

In § 41 (*b*) it was shown that, by Ampère's Rule extended and applied, by aid of Newton's III Law[1], to the case of a conductor moved across a magnetic field, we could understand the production of an E.M.F. (and hence a current) in the conductor and determine its direction. Such a current is called an **induced current.**

We shall find that although there are several ways of inducing a current in a wire, yet there is only one fundamental cause, viz. the *changing of the magnetic field in the neighbourhood of the conductor.*

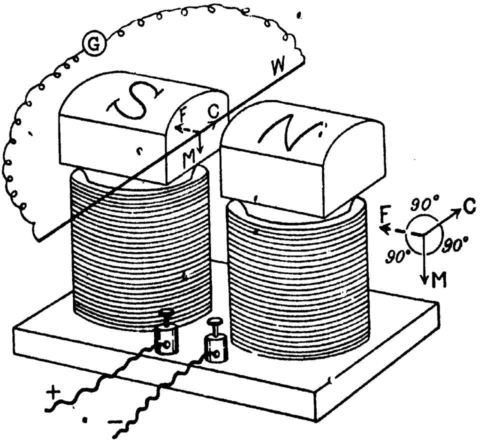


Fig. 92.

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[1] To every action there is an equal and contrary reaction.

Exp. To show that an electro motive force (and hence a **current**) **is produced in a conductor which is moved across the lines of force of a magnetic field**[1].

N and *S* are the two poles (enlarged for purposes of the diagram) of a strong electro-magnet (Fig. 92). *W* is a wire with its ends in circuit with a remote mirror galvanometer (*G*) or a milliammeter. The wire, *W*, is moved rapidly downwards in the direction of the arrow *M*. The magnetic lines of force are in the direction *F*, and the galvanometer indicates that an induced current is produced in the direction of the arrow *C*. If (1) the polarity of the field magnets is changed or (2) the wire is moved upwards, the direction of the current is reversed. Apply the extension of Ampère's rule [§ 41 (*b*)] in order to predict *the direction of the current*, or use **Fleming's Right-hand**[2] **Rule**: point the **Fore-Finger** in the direction of the lines of Force of the Field (*F*), and the **thumb** in the direction of the **motion** (*M*) of the wire, then the **second finger** held at right angles to the plane of the thumb and fore-finger points in the direction of the induced current.

55. Current induced by changing the field.

Exp. (i). Try the effect of keeping the wire stationary between the poles, and then (1) suddenly produce a magnetic field (*F*) by switching on the current in the electro-magnet circuit; (2) break the current. The result reveals the fact that a **current is produced in the wire** (*W*) **only when the lines of force** across the wire are **changing**, *i.e.* increasing or diminishing; the currents in the two cases are in opposite directions.

Induced currents in parallel wires.

Exp. (ii). Remove the electro-magnet and replace it by a wire stretched parallel and close to *W* but not touching it. Switch on a strong current: the galvanometer gives a kick in one direction as before [Exp. (i)] and then returns to its first position. Break the current: the galvanometer kicks in the opposite direction and comes to rest in its first position. Again the deduction is made that a current is *induced* in the wire *W* when the *magnetic lines* of force, caused by the current passed through the parallel wire, are *changing*. This exp. may be *varied* by (*a*) bringing the parallel current-bearing wire up to *W*, and (*b*) removing it.

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[1] This exp. is amplified in § 95, the Dynamo, under the heading "Earth Inductor."

[2] The writer's advice to teachers of beginners is to leave Fleming's Left-hand Rule alone.

56. Effect of increasing or decreasing the magnetic lines of force through a coiled wire.

There are three simple methods of creating an increase or decrease of a magnetic field within a coil:

(*a*) bringing up to or removing a magnet (or an electro-magnet) from the fixed coil;

(*b*) switching on or off the current of an electro-magnet placed opposite or within the fixed coil;

(*c*) turning the coil so as to receive more or less magnetic lines of a fixed field.

Before reading the descriptions of the following experiments the student *should* treat the above statements as problems and *try to devise methods* of demonstrating their truth for himself. He would thereby re-discover Faraday's great discoveries of the years 1830–32 about induced currents.

Exp. (1). To demonstrate (*a*) above.

The arrangement is indicated in Fig. 93, where the N-pole of a bar magnet is brought rapidly up to a coil of (say) 100 turns of thin wire connected to a mirror galvanometer or a microammeter placed at a considerable distance away from the disturbing field of the moving magnet.

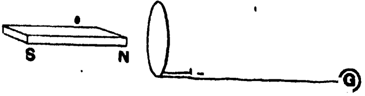

Fig. 93.

Substitute an electro-magnet for the bar magnet.

Observations. (1) The current as indicated by the movement of the galvanometer is induced in the coil only when the number of lines of force entering or leaving the coil is *changing*.

(2) The two induced currents are in opposite directions.

(3) The direction of the lines of force caused by the induced current opposes the direction of the lines of force of the magnet which causes induction. Apply Newton's III Law, viz. "To every action there is an equal and contrary reaction."

Exp. (ii). To demonstrate (*b*) above.

Fig. 94 shows the arrangement. Two coils *A* and *B*, of about 100 turns each, are first placed opposite to each other, *A*'s external diameter being, for experimental purposes only, less than *B*'s internal diameter. *A* the **primary** coil is connected to a battery with a key *K* in the circuit. *B* the **secondary** coil is connected to a remote sensitive galvanometer *G*.

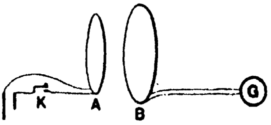

Fig. 94.

Observations. (1) A current is induced in *B* in one direction when the circuit in *A* is completed or "made" at *K*, and in the *opposite* direction when the current in *A* is "broken." It is during the "*making*" and the "*breaking*" of the *primary* circuit that the *lines of force are changing* and the opposite currents are induced.

(2) Carefully note the *direction of winding of the two coils* and the *direction of current*, hence by Ampère's Rule find the direction of the lines of force. It will be found that the induced current (secondary) creates a field opposing that of the primary circuit. [Cf. Exp. (i) 3.]

Repeat the exp. with the coil *A* within the coil *B*.

Exp. (iii). To demonstrate (*c*) above.

Place the coil *B* with its plane in the direction of the lines of force between the poles of a strong electro-magnet (Fig. 92). Rotate the coil about a vertical axis (1) through an angle of 180°; then (2) through another 180° until the coil has resumed its first position. There is an induced current in each half of a complete rotation but the two have opposite directions. Explain this *firstly* by the increase and decrease of the lines of force entering the coil; and *secondly* by Ampère's Rule extension or by Fleming's Right-hand Rule with reference to a conductor cutting through lines of force. [See Earth Inductor, § 95.]

Effect of introducing Soft Iron into the Coils.

Repeat the induction experiments, introducing a soft iron core or bundle of soft iron wires into the coils or solenoids used. Owing to the high *permeability* of iron, the change in the number of lines of force is greatly increased by the introduction of the soft iron core with a consequent great increase in the secondary currents induced on both "making" and "breaking" the primary circuit. This is especially noticeable in Exp. (ii), latter part, where the coil *A* is placed within the coil *B*: in this experiment it is evident that the induction depends not only (i) on the *change in the number of lines* of force but also (ii) on the *rapidity with which the change takes place.*

57. Laws of Induced Currents.

It is well to bear in mind that the current in the secondary coil depends upon the resistance. A secondary coil of fine wire of many turns will furnish a very small current but at high pressure (E.M.F.). Hence in stating the laws of Induced Currents it is best to consider the E.M.F. rather than the current in the secondary coil.

The *induced* E.M.F. in the secondary coil is *proportional* to: (i) the *number of turns* and (ii) the *rate of change of the number of lines of force.*

Lenz's Law. The direction of the induced current is such that it produces lines of force which oppose the lines of force causing the induction. [This follows from Newton's III Law.]

58. The Induction Coil is an elaboration of the apparatus used in § 56, Exp. (ii), where one core (the primary) was placed inside another (the secondary). The **primary** coil (Fig. 95) is

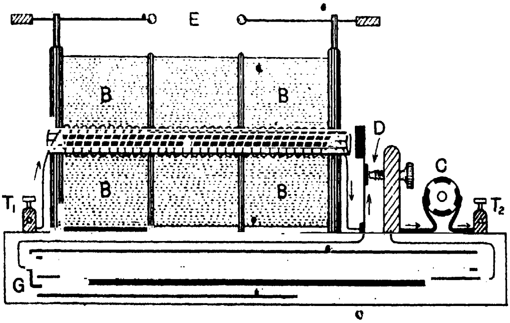

Fig. 95. *AA*, Primary Coil surrounding core of soft iron wires. *BB*, Secondary Coil. *C*, Commutator. *D*, Contact Breaker. *E*, Spark Gap between terminals of secondary coils. *G*, Condenser.

of thick wire wound in (say) three layers round a core of soft iron wires. The **secondary** is fine insulated copper wire (No. 36) wound in layers and sections insulated from each other, and terminates in two adjustable knobs between which the spark travels. The primary current from a battery passes from T_1 through the coil to the **contact breaker,** a spring vibrating on the same principle as the hammer of an electric bell, and thence through a *commutator* to the terminal T_2 which is joined to the battery. A **condenser** [§ 91], consisting of layers of tin-foil separated by paraffined paper, is inserted with one of its two sets of plates on either side of the gap of the contact breaker. The condenser acts as a kind of reservoir into which the electrons forming the primary current flow when contact is "made" and in which they surge to and fro when contact is "broken." The inflowing process takes much longer than the surging rush that follows the "break," for when the current is "broken," it not only ceases to flow in its original direction from the battery, but actually flows back from the condenser in the opposite direction. The induced E.M.F. in the secondary varies with the rate at which the current in the primary is changing [§ 57], and therefore, since the "make" is relatively slow, the induced E.M.F. is smaller at the "make" than at the "break": in fact the spark gap may be lengthened so that no spark jumps the gap at the "make," but only at the "break." The current in the secondary across the gap is then in *one direction only.* The *condenser* also prevents excessive sparking at the contact breaker by acting as a sort of sponge-like buffer for the reception of electrons as they surge backwards and forwards, filling and emptying the reservoir at the "make" and "break" [§ 91].

59. Transformers are modified induction coils.

We shall learn later [§ 98] that high pressure **alternating currents** can be carried long distances more economically than low pressure ones. *Transformers are generally used at various places along the main cable to change the alternating current from a higher to a lower voltage.* Such transformers are called "step-down" transformers, but a "step-up" transformer is used where the reverse process is needed. If the core of an induction coil were bent into the form of a closed ring and an *alternating* current, a stream of electrons rushing or surging first in one direction and then in the opposite direction, were passed through the primary, a corresponding alternating current would be induced in the secondary with each change of direction of the magnetic lines of force through the ring. The E.M.F. in the two coils is in proportion to their respective number of turns (**n**), *i.e.*

$$\frac{\textbf{Voltage in primary}}{\textbf{Voltage in secondary}} = \frac{\mathbf{n}_{\text{primary}}}{\mathbf{n}_{\text{secondary}}}.$$

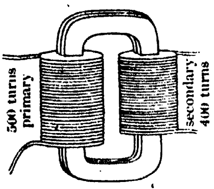

Fig. 96. Step-down transformer 5/4.

Fig. 96 gives a diagrammatic view of a transformer: the coils however may extend round the whole core which is usually made of thin plates (laminae) of soft iron and is either rectangular or circular.

QUESTIONS ON CHAPTER V

1. Describe simple experiments and state rules to illustrate (*a*) the motion of a magnetic pole round a wire carrying a current, (*b*) the motion of a current-bearing wire in a magnetic field.

2. A current passes down a wire perpendicular to the plane of the paper. How would this wire move under the influence of a magnetic field whose direction is parallel to the top of the page from left to right?

3. A wire, coiled round the edges of this page and pivoted about a vertical central line down the page, carries a current flowing in a clockwise direction. Clearly explain the motion which ensues under the influence of a magnetic field whose direction is from left to right parallel to the lines on this paper.

4. An electric car travels due E. with the current flowing downwards through the trolley pole. State (*a*) the direction in which a N-pole would tend to move round the trolley pole, (*b*) the direction in which the trolley pole would tend to move in the earth's field, (*c*) the direction of the current induced in the trolley pole when the car is travelling downhill with the main current switched off.

5. Describe the action of Barlow's wheel, drawing a careful sketch. If the battery is removed and the circuit completed, what is the effect of mechanically rotating the wheel?

6. Two flat coils are placed parallel to one another with their faces close together. State what effects the coils will exert on one another when a current is passed (*a*) in the same direction, (*b*) in opposite directions round the coils. Illustrate with suitable diagrams. L. M. 1920.

7. A current from a battery flows along two horizontal parallel wires, the circuit being completed by a straight wire resting perpendicularly across the parallel wires. State the direction in which this wire would tend to move and explain by aid of a diagram.

8. Describe some simple experiments which illustrate the production of induced currents and state clearly the laws giving (*a*) the direction of the induced current, (*b*) the magnitude of the induced E.M.F.

9. State Lenz's Law. A flat circular coil is connected to a sensitive microammeter. A bar magnet, N-pole foremost, is (*a*) brought near the coil, (*b*) inserted into the coil, (*c*) slipped completely through and withdrawn. Describe the effect on the galvanometer during each stage of the operation. How would the galvanometer be affected if the coil and the axis of the magnet are in the same plane?

10. Draw a clear sketch and explain the action of an induction coil, stating definitely the functions of (*a*) the contact breaker, (*b*) the soft iron core, (*c*) the secondary coil. Explain why there is not an alternating current in the spark gap between the terminals of the secondary coil.

11. Explain the construction and action of a transformer.

CHAPTER VI

ELECTROLYTIC EFFECT OF THE ELECTRIC CURRENT

60. Electrolytes and Electrolysis.

So far our experience has been for the most part with the passage of electricity through *metals*. We are familiar with the use of iron and copper wires for conveying current, and in our experiments with the voltaic cell we were probably more impressed by the effect produced by joining the *wires* than by the equally important part that the *solution* in the cell plays in completing the circuit through which electrons travel. We noticed too that the energy of the cell was derived from the chemical change brought about by zinc dissolving in sulphuric acid *solution*, accompanied by the liberation of hydrogen from the copper plate. The fact that the circuit was completed through the *solution* suggests that we should try **to find what liquids conduct electricity** and what are the **accompanying conditions and results.**

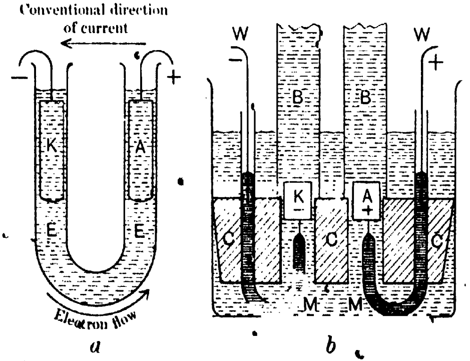

Fig. 97. *A*, Anode. *BB*, Burettes or test-tubes. *CC*, Section of cork. *EE*, Electrolyte. *K*, Kathode. *MM*, Glass tube holding mercury. *WW*, Wires from battery.

Exp. or **Demonstration** (1).

Using a battery of 4 accumulators[1] in series, with an ammeter registering to (say) 2 ampères in the circuit, and a piece of **platinum**[2] foil attached to each end of the two leading wires, try the effect of dipping the *platinum ends* (Figs. 97 *a* and *b*), which *should not touch each other*, into the following liquids:

	Observations.	*Deductions.*
(*a*) petroleum (mineral oil)		
(*b*) distilled water		
(*c*) water + sulphuric acid (H_2SO_4)		
(*d*) water + alkali (say NaOH)		
(*e*) copper sulphate solution ($CuSO_4$ aq.)		
(*f*) silver nitrate solution ($AgNO_3$ aq.)		
(*g*) hydrochloric acid solution[3] (HCl aq.)		
(*h*) common salt solution[3] (NaCl aq.) to which a few drops of phenolphthallein have been added		

The platinum ends leading to and from the battery are called **Electrodes.**

The electrode connected to the –^{ve} **pole** is called the **kathode.**
„ „ „ +^{ve} „ „ **anode.**

Summary of results. You will find that *oils* (*a*) and distilled *water* (*b*) do not conduct electricity and there is no chemical reaction; but *acids* (*c* and *g*), *alkalies* (*d*) and *salts* (*e*, *f* and *h*) *in solution* are *conductors* and that *chemical changes* involving *decomposition* of the liquid accompany the passage of electricity. Note that *hydrogen* or a *metal* is liberated at the *kathode.*

The process of decomposing a liquid by passing electricity through it is called **electrolysis** (*lit.* loosening by electrons).

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[1] Grove Cells or Chromic Acid Cells will serve the purpose. If current from the "main" [generally at 220 or 110 volts] is used, insert one or two 32 c.p. carbon filament lamps in parallel: these are useful to indicate whether current is flowing, and also to give the necessary resistance. **Caution:** do not switch on the current until all is ready and **do not touch the wires**, etc., while current from the mains is passing.

[2] If platinum electrodes are not obtainable, use carbon rods (arc "pencils"), see Figs. 101 and 100.

[3] Use carbon anodes: Chlorine attacks Platinum.

Liquids which conduct electricity and at the same time undergo chemical decomposition are called **electrolytes.**

Demonstration (ii).

Using a battery of 4 (4-volt) accumulators or the "main" supply [see note, p. 105], connect in series with the five electrolytic cells, shown in Fig. 98, viz. (1) dilute sulphuric acid, (2) copper sulphate, (3) silver nitrate, (4) hydrogen chloride, (5) sodium chloride (common salt). [The electrodes are platinum except the anodes of cells (4) and (5) which are gas-carbon because the gas *chlorine* liberated at these anodes attacks platinum: *chlorine* is soluble in water; it is therefore necessary to saturate solutions (4) and (5) previously with chlorine gas.]

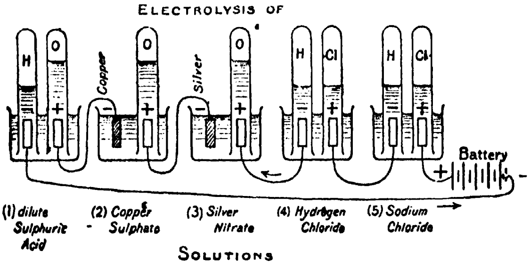

Fig. 98.

Observations: (*a*) Equal volumes of *Hydrogen* are liberated at the *kathodes* of cells (1), (4) and (5);

(*b*) the same volume of *Chlorine* (as of Hydrogen above) at the *anodes* of cells (4) and (5);

(*c*) half this volume of *Oxygen* at the *anodes* of cells (1), (2) and (3);

(*d*) the *metals* copper and silver respectively are deposited at the *kathodes* of cells (2) and (3). After some time metal ceases to be deposited, the colour of the copper sulphate is perceptibly lighter and the current falls off but is renewed on addition of more of the metallic salt, when metal is again deposited;

(*e*) the metal *sodium* is not deposited at the kathode of cell (5) as we should have expected by analogy with (2) and (3), because of a secondary reaction of sodium with water whereby the alkali sodium[1] hydroxide is formed and hydrogen liberated [$2Na + 2HOH = 2NaOH + H_2$].

Deductions.

The **same current** has passed through each cell for the **same time.** Equal volumes of Hydrogen (density 1) and Chlorine (density 35·5) were liberated and half the volume of Oxygen (density 16). Therefore the weights of these gases liberated by the *same current* are in the proportion of 1 : 35·5 : 8, which corresponds to their chemical **equivalent weights.**

If, before and after the Exp., we had weighed the two kathodes (2) and (3) on which *copper* and *silver* were deposited we should have found an increase of weight corresponding to their chemical equivalents, viz. 31·5 and 108 times respectively the weight of hydrogen liberated.

61. Faraday's Laws of Electrolysis.

I. *The amount of chemical reaction in a circuit is the* **same** *at all points.*

II. *The* **weight** *of substance liberated at an electrode is* **proportional** *to the* **strength** *of the* **current** *and the* **time** *during which it flows (i.e. proportional to the* **quantity** *of electricity).*

III. *If the* **same quantity** *of electricity passes through a series of electrolytes, the* **weights** *of the substances liberated are* **proportional to their equivalent weights.**

Combining Laws II and III, viz. that the weight of a substance liberated is proportional to the quantity of electricity passed and selecting the unit quantity in each case, we introduce a new term, the **electro-chemical equivalent,** to indicate for each substance **the weight liberated by unit quantity of electricity.**

---

[1] **Pole-Testing Paper.** The presence of the *alkali* may be shown by the addition of phenolphthallein to an electrolyzed salt solution: the solution turns *reddish-pink. Pole-testing paper* is made by drying filter paper previously soaked in a solution of salt and phenolphthallein. *Use:* moisten the paper and touch it with the two terminals from the battery or "main" wires: a red stain appears at the negative pole where alkali is formed.

The *unit quantity* of electricity, in *practical* units, is an **ampère per second** and is called a **coulomb.** The *electro-chemical* equivalent ($\mathbf{e}$) of an element will therefore be expressed in **grams per coulomb,** *i.e.* the weight of each particular element liberated by one ampère in a second.

I.e. $$W = \mathbf{e}Ct$$

where W = weight in grams of the element deposited,
$\mathbf{e}$ = the electro-chemical equivalent of the element,
C = current in ampères,
t = time in seconds.

Further, if

$\mathbf{e}_{\text{hydrogen}} = \cdot 0000104$ gram per ampère per sec.
then $\mathbf{e}_{\text{any element}} = \cdot 0000104 \times$ element's chemical equivalent,
e.g. $\mathbf{e}_{\text{copper}} = \cdot 0000104 \times 31\cdot 5 = \cdot 000329.$
$\mathbf{e}_{\text{silver}} = \cdot 0000104 \times 108 = \cdot 001118.$

Exp. (1). To find the electro-chemical equivalent of copper. (Galvanometer method.)

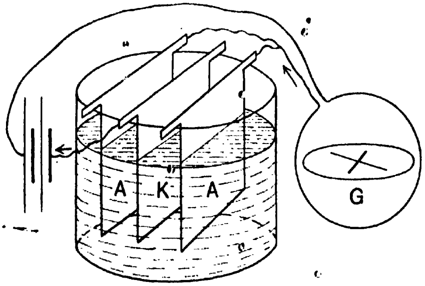

Fig. 99.

Remember $W = \mathbf{e}Ct$. Set up a circuit (Fig. 99) consisting of two accumulators (or 2 Bichromate Cells or 4 Daniell's Cells), a tangent galvanometer (G) (or accurate ammeter registering to 1 or 2 ampères) and an electrolytic cell

(AKA) of copper plates in a solution of copper sulphate[1]. A watch recording *seconds* is needed. The copper plates of the electrolytic cell are carefully cleaned by dipping in dilute nitric acid and afterwards scrubbing them in pure water. A preliminary trial without weighing the plates should be made, passing current in each direction in order to obtain a good deposit of copper on the electrodes. The kathode is then removed, washed in (1) distilled water and (2) alcohol and afterwards dried in hot air[2].

The *kathode* is then weighed :

77·942 grams ....(1).

The kathode is then placed between the two plates AA which form the anode and the circuit is completed. Readings are taken every minute at both ends of the galvanometer pointer and the mean of the 30 readings at the end of 15 minutes (**900 secs.**) calculated. Mean **deflection** $\theta = 31°$. The kathode is then removed, washed with (1) water, (2) alcohol, dried and weighed as before :

77·98 grams ....(2).

Weight of Copper deposited (2) − (1) **·038** gram.

Reduction factor of galvanometer [§ 45] = 0·209.

Current in ampères $= \cdot 209 \times \tan 31° = \cdot 209 \times \cdot 601$

$= \mathbf{0 \cdot 1256}$ **amp.**

∴ 0·1256 ampère in 900 secs. liberates ·038 gram of copper.

$$\therefore \text{ 1 ampère in 1 sec. liberates } \frac{\cdot 038}{\cdot 1256 \times 900}$$

$= \mathbf{\cdot 00033}$ gram of copper (approx.).

∴ the **electro-chemical equivalent of copper** is **·00033.**

Exp. (ii). To find the chemical equivalent of copper and hence the **electro-chemical equivalent of hydrogen.** (Voltameter method.)

Substitute an electrolytic cell of dilute sulphuric acid with platinum electrodes for the galvanometer, and also increase the voltage of the battery to 6 or 8 volts[3]. Collect and measure the hydrogen evolved (V c.c.) at the kathode of the acid cell (Fig. 100) [note the temperature (t) and the pressure (p)[4]]. Weigh the copper deposited (W_{Cu}) on the kathode of the $CuSO_4$ cell as in Exp. (i). Assuming, for *approximate* results, that 1 c.c. of Hyd. weighs ·000085 gram[4], we obtain the weight of Hyd. (W_{Hyd}) evolved $= \cdot 000085 \times V$. Then, since

---

[1] The anode dissolves, but *copper deposits on the kathode*; the strength of the $CuSO_4$ solution remains constant.

[2] Some distance above the Bunsen flame.

[3] If the "main" supply is used put two 32 c.p. carbon filament lamps in parallel into the circuit.

[4] For accurate results, correct the Vol. observed to V_0 at S.T.P. at which 1 c.c. of hydrogen weighs ·00009 gram.

W_{Cu} grams of Copper and W_{Hyd} grams of Hydrogen were liberated by the same current, and the Chemical Equivalent of Hydrogen $=1$,

$$\frac{W_{Cu}}{W_{Hyd}} = \text{Chemical Equivalent of Copper} = 31{\cdot}5 \text{ approx.}$$

Assuming the result of Exp. (i), then

$$\frac{\text{Electro-chemical Equivalent Hydrogen}}{\text{Electro-chemical Equivalent Copper}} = \frac{\text{Chemical Equivalent Hydrogen}}{\text{Chemical Equivalent Copper}}.$$

$$\therefore \frac{\text{Electro-chemical Equivalent Hydrogen}}{\cdot 00033} = \frac{1}{31{\cdot}5}.$$

∴ **Electro-chemical Equivalent Hydrogen**

$$= \frac{\cdot 00033 \times 1}{31{\cdot}5} = \mathbf{\cdot 0000104.}$$

Voltameters.

An electrolytic cell used for the *measurement of current* is called a Voltameter; *e.g.* a copper voltameter and a hydrogen voltameter in the last experiment. If we know the *electro-chemical equivalent* (**ε**) of the element liberated, its *weight* (**W**), and the *time* (**t** sec.) during which the current passes through the voltameter, we obtain the **current** in ampères by applying the formula

$$C = \frac{W}{\epsilon t}.$$

We can therefore apply the Voltameter method for:

(*a*) *measuring current,*

(*b*) finding the reduction factor of a tangent galvanometer, and

(*c*) standardizing an ammeter.

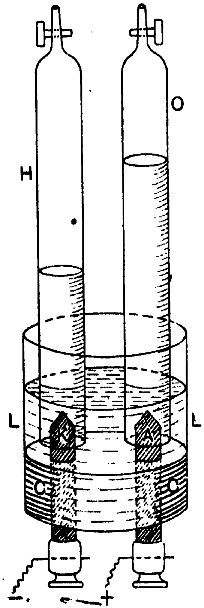

Fig. 100. *LL*, Lamp-glass. *CC*, Perforated cork. *KA*, Kathode and Anode of Carbon (arc-pencils). *H*, 2 vols. Hydrogen. *O*, 1 vol. Oxygen. Electrolysis of dil. H_2SO_4.

The student should check his results of § 45 or of Experiments where an ammeter was used by the Voltameter method.

TABLE OF ELECTRO-CHEMICAL AND CHEMICAL EQUIVALENTS.

Element	Atomic Weight	Valency	Chemical Equivalent	Electro-chemical Equivalent = grams per ampère per sec.
K. Hydrogen	1	1	1	0·0000104
Sodium	23	1	23	0·0002384
Copper (divalent)	63	2	31·5	0·0003295
Zinc	65	2	32·5	0·0003387
Silver	108	1	108	0·0011183
Lead	207	2	103·5	0·0010728
A. Oxygen	16	2	8	0·0000829
Chlorine	35·5	1	35·5	0·0003675

Definition of the Ampère on the basis of electrolysis. An ampère is the practical unit of current which flowing for 1 second liberates 0·0011183 gram of silver. An ampère = $\frac{1}{10}$ electro-magnetic unit of current.

62. Electrolysis applied commercially.

(1) *Electroplating and electrotyping.*

Electroplate of various kinds, especially jewellery, ornaments and table utensils, is familiar to everyone. Gold, silver, copper, nickel and several other metals are deposited electrolytically from a suitable solution. Gold and silver are dissolved as the double cyanide of the metal and potassium.

Exp. Add potassium cyanide very gradually to a solution of silver nitrate until the first precipitate of silver cyanide is just dissolved. The solution of silver potassium cyanide is a suitable "bath" for the deposition of silver on (say) a copper candlestick or a britannia metal spoon. The latter, previously cleaned by scouring with sand and soda, is washed and placed in the "bath" as the *kathode*; a small piece of sheet silver as anode replenishes the solution by dissolving at the same rate that silver is depositing on the article to be plated [cf. Exp. § 61]. A moderate but steady current at from 2 to 4 volts pressure is passed until a sufficient thickness of plating is deposited when the article may be removed, dried and polished.

Electrotyping is a process for reproducing type, seals, coins, cameos, etc. The method is as follows:

(*a*) obtain an impress of the object in wax or plaster;

(*b*) render the inside surface of the impression conducting by dusting with graphite[1] or powdered bronze;

(*c*) make a copper shell of the impression by depositing copper electrolytically in a "bath" of copper sulphate;

(*d*) remove the wax and strengthen the shell, which acts as a mould, by pouring in melted type metal or other fusible alloy.

(2) *Purifying smelted copper* by dissolving the ingots, which are used as *anodes*, in the electrolytic bath of copper sulphate solution, and depositing the pure copper on suitably shaped copper *kathodes*.

(3) *Electrolysis at high temperatures: e.g.* extraction of *aluminium* from alumina and the fused double chloride of aluminium and sodium using carbon electrodes. When the electrolyte is once fused the heat is maintained by the passage of electricity.

63. Elementary Theory of Electrolysis.

There are reasons for supposing that electrolytes dissociate in dilute solutions into their constituent *ions* [§ 16], called respectively *kations* or *anions*, as they travel towards the *kathode* or the *anode*, charged, with electrons in defect, *positively* on the one hand or, with electrons in excess, *negatively* on the other.

Faraday in 1833 suggested that chemically equivalent atoms carried equal charges of electricity. This we can express by equations such as the following:

$$\begin{array}{lcll} & & +^{\text{ve}}\text{ Ion or} & -^{\text{ve}}\text{ Ion or} \\ & & \text{Kation} & \text{Anion} \\ H_2SO_4 & \rightleftarrows & \begin{matrix} H^{-\epsilon} \\ H^{-\epsilon} \end{matrix} & SO_4{}^{+\epsilon}_{+\epsilon} \\ KCl & \rightleftarrows & K^{-\epsilon} & Cl^{+\epsilon} \\ CuSO_4 & \rightleftarrows & Cu^{-\epsilon}_{-\epsilon} & SO_4{}^{+\epsilon}_{+\epsilon} \end{array}$$

---

[1] The conducting surface is improved by washing it with copper sulphate and afterwards sprinkling with finely divided iron, which, by displacement, covers the surface with a layer of copper.

where $-\epsilon$ represents an electron in defect
and $+\epsilon$,, ,, excess.

We have learnt in § 14 that in a battery of voltaic cells, electrons accumulate on the zinc plate and at the $-^{\text{ve}}$ pole: correspondingly there is a defect of electrons at the $+^{\text{ve}}$ pole. If two carbon electrodes in a solution of *common salt*, sodium chloride, are joined to the two poles of a battery (Fig. 101), the accumulation of electrons on the zinc plate is carried into the solution at the kathode (*K*) and a defect of electrons appears at the anode (*A*). Since however "unlike charges attract each other,"

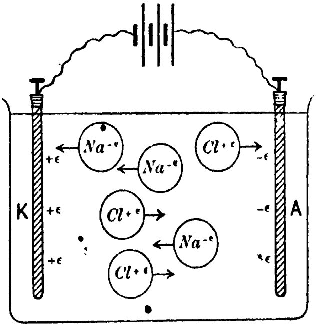

Fig. 101. Migration of Ions.

the $-^{\text{vely}}$ charged *chlorions*, $Cl^{+\epsilon}$, migrate towards the $+^{\text{vely}}$ charged *anode* where they lose their charge by neutralization $(+\epsilon-\epsilon)$ and are liberated in pairs as chlorine molecules. Similarly the *sodium-ions*, $+^{\text{vely}}$ charged, $Na^{-\epsilon}$, migrate towards the $-^{\text{vely}}$ charged *kathode* where they lose their charge by the addition of an electron per ion, and would be deposited as molecules of sodium, if they did not immediately react chemically with the water forming a solution of sodium hydroxide with the liberation of hydrogen

$$2Na + 2HOH = 2NaOH + H_2.$$

The energy of the battery is therefore used in liberating electrons, which in turn overcome the resistance of the circuit which includes the electrolytic cell where the two sets of ions are caused to migrate in opposite directions.

64. Back E.M.F. (The principle of the accumulator.)

The student should revise § 17 where the subject of "back E.M.F." in the voltaic cell is first mentioned.

Exp. (i). Show that the E.M.F. of a single Daniell's cell is not sufficient to electrolyze dilute sulphuric acid. Connect the platinum electrodes of Fig. 97 *a* to a Daniell's cell: a few bubbles appear at the electrodes but current soon falls to zero. Two or three cells in series are found to be sufficient for electrolysis.

Show that there is a back E.M.F. from the electrodes by quickly switching them in circuit with a sensitive galvanometer—*e.g.* the mirror galvanometer of § 44: the current is found to be in the opposite direction to the battery current. The separated oxygen and hydrogen condensed on the anode and kathode respectively produce for a time an opposing potential difference until recombination can take place by transference of electrons that have accumulated.

Exp. (ii). Repeat Exp. (i) substituting strips of **lead**[1] as electrodes. Continue electrolysis for ten minutes: then show by connecting the electrodes to a galvanometer[2] that the back E.M.F. is more sustained than in Exp. (i).

Accumulators or Storage Cells or Secondary Cells.

Planté in 1860 showed that a secondary cell could be built up, by charging in alternating directions, and discharging, the lead electrodes of the last experiment, which retained its charge and could sustain an electromotive force of about 2 volts through a high resistance for some considerable time. An indication of the reactions of charging and discharging the plates is given by the following equations:

At the anode (1) $Pb + O_2 \rightleftarrows PbO_2$.

At the kathode (2) $Pb + xH \rightleftarrows$ condensed or occluded hydrogen on lead.

---

[1] Spongy lead, obtained by putting thin strips of pure zinc in a solution of acetate of lead, makes the best electrodes for this experiment.

[2] A galvanoscope, § 42, or even an electric bell may be used to show the back E.M.F. if large lead plates are used as electrodes.

Fauré in 1880 discovered that a much more efficient secondary cell was rapidly built up by using lead plates pitted with holes filled with a paste of (1) *red lead* (Pb_3O_4) mixed with strong sulphuric acid for the *anode* (+ᵛᵉ) and (2) *litharge* (PbO) and sulphuric acid for the *kathode* (–ᵛᵉ). The reactions approximate to the following equations:

$$(1)\ Pb_3O_4 + 2O = 3PbO_2 \text{ on first charging.}$$

$$PbO_2 + H_2SO_4 \rightleftarrows PbSO_4 + H_2O + O. \quad \text{[Anode.]}$$

$$(2)\ PbO + 2H \rightleftarrows Pb + H_2O. \quad \text{[Kathode.]}$$

The plates of the modern **accumulator** [E.M.F. = 2·1 volts] are made of lead in the form of an open grid, the spaces being filled with a compressed paste of red lead and sulphuric acid. The process of charging *oxidizes* the *positive* plate to *lead peroxide* (PbO_2) and *reduces* the *negative* plate to spongy *lead*. During *discharge* lead sulphate ($PbSO_4$) is formed so that the *solution* loses sulphuric acid and becomes *less dense* (1·18 approx.), but on *charging* its *density increases* (1·210 approx.). The *voltage* may range from 2·3 to 2 volts but should not be allowed to fall below 2 volts without recharging. The accumulator gives best results if kept in constant use, but care should be taken to avoid any sudden fall of potential by short-circuiting.

QUESTIONS ON CHAPTER VI

1. Carefully state and explain Faraday's "Laws of Electrolysis" and describe any experiments you would make to illustrate the truth of these laws.

2. Write a careful account of what takes place when an electric current is passed through an acidulated solution of water. Why is this operation often termed the "electrolysis of water"?

3. Two carbon rods are placed separately in test-tubes containing a solution of common salt (NaCl) to which a few drops of litmus have been added. The tubes are united by a wet strip of blotting paper. Account for the changes which take place when a current is passed through the tubes using the rods as electrodes.

4. Define the terms "electrolyte," "electro-chemical equivalent." State exactly what is meant by the statement that the electro-chemical equivalent of hydrogen is ·00001038 and calculate the amount of copper deposited from copper sulphate solution by a current of 3 ampères in half an hour.

(Chemical equivalent of copper = 31·6.)

5. Describe an experiment to determine the electro-chemical equivalent of hydrogen with full details of the precautions necessary to obtain an accurate answer. What is meant by "back E.M.F." and how does the back E.M.F. influence the success of this experiment?

6. What is a "voltameter"? Describe its use and advantages as an accurate current measurer, giving full experimental details.

7. Describe how you would carry out experiments with a copper sulphate voltameter to show that the quantity of copper deposited in a given time is

(*a*) directly proportional to the strength of the current,

(*b*) independent of the size of the electrodes and the strength of the solution. O. L. J. 1920.

8. Calculate the current used in the following experiment with a copper voltameter.

Weight of kathode before experiment = 20·10 grams.
,, ,, after ,, = 21·284 grams.
Time of experiment = ½ hour. E.C.E. of copper = ·000329.

9. Calculate the Reduction Factor of a Tangent Galvanometer from the following data:

Weight of kathode before experiment = 18 grams.
,, ,, after ,, = 18·395 grams.
Time of experiment = 20 mins. Deflection of galvanometer = 30°.
E.C.E. of copper = ·000329.

10. Give a detailed account of the "Theory of Electrolysis."

A copper voltameter containing copper sulphate solution and copper electrodes and a silver voltameter containing silver nitrate and silver electrodes are connected in series and a current is passed through them. Describe what takes place in each vessel and give the relative proportions of copper and silver set free by the current. (The at. wts. of copper and silver may be taken as 63 and 108 respectively.) Lond. Univ. 1920.

11. A current is passed for 22 minutes through a silver voltameter in series with a tangent galvanometer of 10 turns, and radius 10 cms. The deflection of the galvanometer needle is 45° and ·423 gm. of silver is deposited. What value does this give for the E.C.E. of silver? ($H = \cdot 18$, $\pi = \frac{22}{7}$.)

12. Describe the process known as "electroplating." It is desired to plate with silver a metal spoon. Would it be sufficient to place the spoon anywhere in a solution of a silver salt through which a current is passing?

13. Describe the construction of a modern storage battery or accumulator. What changes occur during the process of charging and discharging the cell?

CHAPTER VII

APPLICATIONS OF OHM'S LAW. ELECTROMOTIVE FORCE. RESISTANCE

65. The Student should carefully revise §§ 11–13. The analogy that was drawn between (1) a *current* of water and the electron-flow, (2) the *pressure* of water in a pipe and the electromotive force which forces electrons through a conductor, and (3) the *resistance* of the channel to the passage of water and the resistance in a wire to the electron-flow, was followed by the consideration of the relationship between these fundamental quantities as embodied in **Ohm's Law: the current in a circuit varies directly as the electromotive force and inversely as the resistance of the circuit.**

$$C = \frac{E}{R}.$$

66. The **Voltmeter** is a galvanometer for *measuring difference of electric pressure* or *potential.* It is absolutely necessary for the student to distinguish between a voltmeter and an ammeter. The *ampère-meter measures current*: it is placed *either* directly in

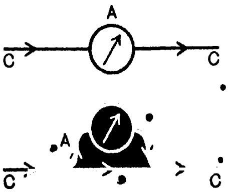

Fig. 102 *a*. **Ammeter** in the main circuit *or* as a definite part of the main circuit.

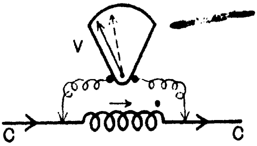

Fig. 102 *b*. **Voltmeter** has so high a resistance that main current is practically unaltered.

the circuit, *i.e.* in series with the battery in which case its *resistance* to the flow of electricity should be exceedingly *small*, *or*, as a shunt, allowing a definite fraction of the current to pass through it, say, $\frac{1}{10}$ or $\frac{1}{100}$ etc. (Fig. 102 *a.*)

A *voltmeter* on the other hand should be of such high resistance that very little current flows through it and the effect of placing it in parallel in the circuit is negligible (Fig. 102 *b*). A tangent galvanometer [§ 45] consisting of a coil of very fine wire with many turns may be used as a Voltmeter; or again a micro-ammeter of the moving-coil type [§ 46], furnished with a high resistance, makes a useful voltmeter.

Exp. (i). To compare the E.M.F.'s of two or more cells.

The high resistance coil of a tangent galvanometer may be used for comparing the E.M.F.'s (E_1, E_2 etc.) of two or more cells by placing the galvanometer and cell in series with a commutator. The mean of four readings must be taken, 2 for each direction of the current through the galvanometer, in order to obtain the true angle of deflection (θ_1, θ_2 etc.). The *resistance* of the coil is so great compared to the resistance of the cell that the total resistance (R) of the circuit remains approximately constant. Then by Ohm's Law:

$$E_1 = R \times C_1 = R \times k \tan \theta_1,$$

$$E_2 = R \times C_2 = R \times k \tan \theta_2,$$

$$\therefore \frac{E_1}{E_2} = \frac{\tan \theta_1}{\tan \theta_2}.$$

Exp. (ii). Place (1) a *Daniell's* Cell, (2) a *Leclanché* Cell, (3) an *accumulator* in series with the high resistance coil of the tangent Galvanometer [§ 45] of (say) 200 turns or the corresponding coil of the galvanoscope [§ 43]. Note the deflection in each case. Assuming the E.M.F. of the cells to be respectively (1) 1·07, (2) 1·4, (3) 2·1 volts, draw a curve for each instrument $\frac{\text{deflection}}{\text{voltage}}$. Use the curve for finding the E.M.F. of (*a*) a voltaic cell, (*b*) 2 Daniell's cells in series, (*c*) a Daniell cell and a Leclanché cell in series.

Exp. (iii). Referring to the grouping of cells, p. 23, devise an experiment to show that the **E.M.F.** of a battery of (*a*) **cells arranged in series is equal to the sum of the E.M.F.'s of all the cells,** (*b*) **cells arranged in parallel is the highest E.M.F. of the set.**

Exp. (iv). To measure the potential difference between two points (say the terminals of a cell) **and to show that the potential difference falls off as the current between the points is increased by lowering the intervening resistance.**

A high resistance tangent galvanometer or a voltmeter is connected between the terminals *A* and *B* of a Daniell cell (Fig. 103), (*a*) when no other wire connects the terminals, (*b*) when a resistance of 50 ohms (a length of approx. 5 ft. of No. 40 German silver wire on a reel), (*c*) when a resistance of 10 ohms (approx. 10 ft. of No. 36 German silver wire) connects *A* and *B*. Read the voltage direct if a voltmeter is used, or tan. ∠ of deflection if the high resistance tangent galvanometer is used. Record your results, and note the analogy of the falling off in water-pressure where one pipe supplies two or more taps when first one tap and secondly two taps are turned on.

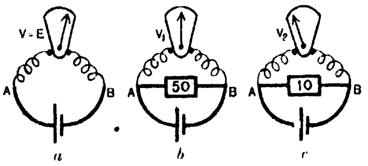

Fig. 103.

***Exp. (v). To adjust a milliammeter for use as voltmeter.**

Place the milliammeter [§ 48] in series with a resistance box of (say) 1000 ohms and a Daniell's cell (1·07 volts): adjust the resistance so that the deflection is 10·7 scale divisions corresponding to the E.M.F. of the Daniell's cell. Confirm the adjustment by replacing the Daniell's by a Clark's Standard cell (1·43 volts): the deflection should be 14·3 divisions.

67. Fall of potential along a wire. [Cf. § 11.]

AB is a uniform wire (No. 32 German Silver[1]) of high resistance stretched over a metre scale between two binding screws *A* and *B* (Fig. 104). A steady current is maintained in *AB* from a battery (Z) of (say) 3 Daniell's Cells when the plug K is inserted. The potential difference between A and B is approx. 3·2 volts.

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* **Omit for first reading.**

[1] **Resistance (approx.) = 3 ohms per foot. See Appendix III.**

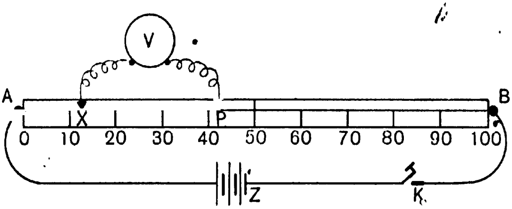

Fig. 104.

To show that there is a constant fall of potential along a uniform wire carrying a steady current.

Exp. i. Connect the two terminals of the high resistance coil of the tangent galvanometer, G, by pressing the connecting wires to any two points X and P on the wire AB so that there is a convenient deflection (say 12°) which indicates a certain potential difference between X and P. Measure *the distance XP* by taking readings on the metre scale. Repeat several times altering the position of X on the scale and obtaining the *same* deflection for a new position of P. The *distance XP* should remain *constant*.

Exp. ii. Connecting X to the binding screw A (Fig. 105), vary the position of Y along the scale, and take readings of (1) the deflection of the

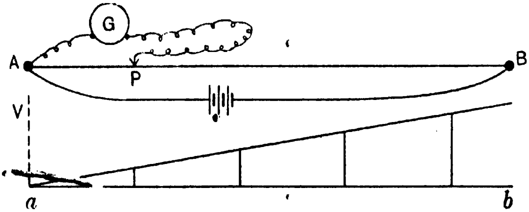

Fig. 105.

galvanometer needle for (?) each position of P. The tangent of the angle of deflection (θ), which is proportional to the current, may be taken to be proportional to the potential difference between A and P. It is found that:

$$\frac{\tan\theta}{AP} = \text{a constant.}$$

Plot the curve $\frac{\text{potential difference}}{\text{distance along wire}}$ with aV and ab as axes.

If we assume the wire to be of uniform thickness and its resistance proportional to its length and that a steady current was maintained then the above equation is equivalent to

$$\frac{\text{Potential Difference}}{\text{Resistance}} = \text{constant},$$

which is a confirmation of Ohm's Law $\frac{E}{R} = C$.

68. Potentiometer method of finding E.M.F.

The long thin uniform wire mounted on a scale the use of which has just been described [§ 67] is called a **Potentiometer.** For convenience the wire is often zig-zagged symmetrically across a board. The essentials are that the *wire* shall be fairly long (2 metres), of *high* but *uniform resistance* and that *distances* along the wire may be *readily measured.*

Exp. To compare the E.M.F.'s E_1 and E_2 of two cells.

The $-^{ve}$ pole of a 4 volt accumulator is connected to A and the $+^{ve}$ pole to B of the potentiometer wire AB (Fig. 106). A steady electron-flow is maintained in the direction AB, and there is a uniform fall of potential from

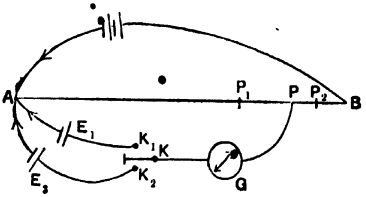

Fig. 106.

A to B. The $-^{ve}$ poles of the two cells E_1, E_2 whose E.M.F.'s are to be compared are connected to A, and their $+^{ve}$ poles, through a 3-way switch, are joined to a sensitive galvanoscope (G) and thence to the point P which is moved along the wire.

Seeing that the negative poles of the cells are joined to A, the electron-flow from the main circuit opposes that of the lower galvanoscope circuit and tends to stop the current or force it in the opposite direction.

If the difference of potential between A and B is greater than the E.M.F. of each of the two cells E_1, E_2, there will be a point P_1 (say) somewhere along the wire such that, when E_1 is connected with it through G the opposing electron-flows will produce equal and opposite pressures at A and the current due to E_1 in the lower circuit will be reduced to zero, *i.e.* there will be no deflection of G when P is connected to the potentiometer wire at P_1. Similarly when E_2 is placed in the lower circuit, no current will pass through G when P is placed at P_2 (say).

Then the fall of potential from A to P_1 = the E.M.F. E_1
and ,, ,, ,, A to P_2 = ,, ,, E_2
and since the fall of potential is constant per unit length along AB

$$\frac{AP_1}{AP_2} = \frac{E_1}{E_2}.$$

69. Resistance.

In our enquiry into the relationship of hydrostatic pressure (P) and current (C), we deduced the constant ratio that exists between the two when the conditions are constant, and we found that this ratio of $\frac{P}{C}$ was a measure of the resistance of the circuit. This was the form in which Ohm originally stated his law, in 1826, when he first investigated the conditions of length, section, temperature and potential on which depend the power of a wire to conduct electricity. If these physical conditions are not changed then the ratio **E.M.F./current** is **constant** for any circuit and is called the **Resistance** of the circuit.

Then $$\frac{\mathbf{E}}{\mathbf{C}} = \mathbf{R}.$$

Resistance is measured in units called **Ohms.**

In the equation $\frac{E}{C} = R$, if R is required in **Ohms,** E must be expressed in **volts** and C in **ampères,** thus

Volts/ampères = Ohms or *Volts = ampères × Ohms.*

The practical definition of an OHM is the resistance of a column of mercury of 1 sq. mm. cross-section and 106·3 cms. in length at 0°C.

This quantity of mercury weighs 14·4521 grams.

N.B. For relationship between Absolute (C.G.S.) units and Practical units see § 79.

Exp. (i). To show that for a given wire the ratio $\frac{E}{C}$ = a constant = the resistance of the wire.

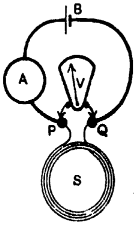

Fig. 107.

A coil (S) of insulated G.S. wire (say 12 yards of No. 32 of approx. 30 ohms resistance) is put in circuit with an ammeter and one Daniell's or accumulator cell (B) [Fig. 107].

The **P.D.** between the ends PQ of the coil S is taken by the voltmeter $V = E$ volts and the **current** is measured by the ammeter $A = C$ ampères. Two, three and four cells *in series* are placed in the circuit. It will be found that the ratio $\frac{\textbf{E volts}}{\textbf{C ampères}}$ remains approx. **constant**, the result being given in **ohms resistance.**

Exp. (ii). To find the resistance of an incandescent lamp by voltmeter and ammeter.

Having established the above ratio as a measure of the resistance, place a suitable voltmeter registering up to 250 volts across the mains terminals.

(**Caution.** If the voltmeter or ammeter has a + sign opposite one terminal, take care to connect this to the positive terminal of the main supply or of the battery used.)

Actual reading, **220 volts.** Place an ammeter in circuit with a 32 candle-power Ediswan carbon filament lamp (replacing S in Fig. 107) and the mains (replacing the battery B in Fig. 107). Actual reading of ammeter, **0·45 amp.**

∴ **resistance** of one 32 c.p. carbon filament lamp

$$= \frac{220 \text{ volts}}{0{\cdot}45 \text{ amp.}} = 488 \text{ ohms (approx.).}$$

Repeat with

(*a*) 2 lamps in *series*. **Result** $R = \frac{220 \text{ volts}}{0{\cdot}225 \text{ amp.}} = 977$ ohms (approx.).

(*b*) 2 lamps in *parallel*. „ $R = \frac{220 \text{ volts}}{0{\cdot}9 \text{ amp.}} = 244$ ohms.

Suitable Laboratory Resistances.

In addition to the Lamp Resistance Board described in Appendix I the following should be briefly explained.

Sliding Rheostat. A thin wire of high resistance wound on a slate cylinder and terminated at each end with a binding screw (Fig. 108) so that the wire may be put in series in the circuit. The current is passed through a longer or shorter length of the wire, *i.e.* through a greater or less resistance, by sliding the contact along the metallic rod which is attached to one of the terminals.

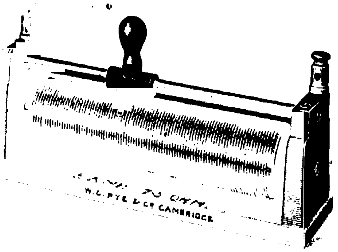

Fig. 108.

Coil Rheostat: consists of a set of coils R_1, R_2, R_3 ... (Fig. 109) which may be brought into series in the circuit by a rotating contact *JAH*, *J* being the junction with the metallic bosses 1, 2, 3...at the ends of the coils, *A* the axis and *H* the handle. Such a set of coil resistances is used on electric trams, motors etc. The energy of the current is dissipated in heating the coils.

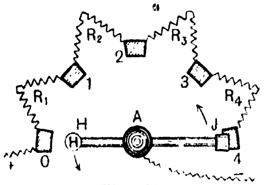

Fig. 109.

Carbon Resistance or Rheostat. Fig. 110 is used with heavy currents and consists of plates of gas-carbon held in contact in an insulated frame.

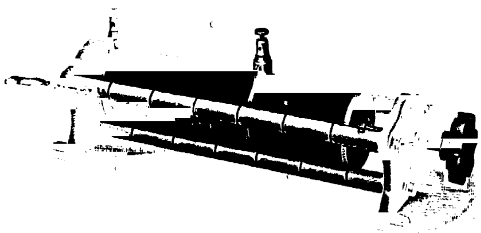

Fig. 110.

Circuit is completed through two adjustable plates that may be inserted between the carbon plates and contact is loosened or tightened by means of an insulated screw at the end of the frame.

Liquid Resistance. A useful form of variable resistance for large currents consists of two carbon pencils or plates, (one fixed, the other adjustable and set in a movable board), placed in a solution of copper sulphate or other suitable electrolyte (Fig. 111). It must be remembered that (1) part of the drop in current is due to back E.M.F. of electrolysis [§ 64]; (2) the solvent requires replenishing.

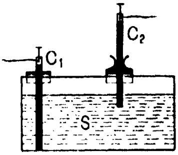

Fig. 111. C_1, Fixed carbon pencil. C_2, Adjustable pencil. S, Solution of Copper Sulphate.

Resistance Coils and Resistance Boxes.

The student should construct a one-ohm, two-ohm and a five-ohm resistance coil [see Wheatstone's bridge, § 73] using Manganin or Constantin wire.

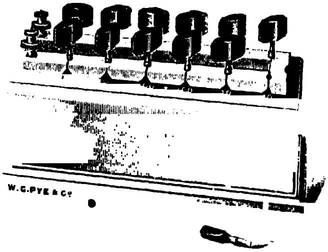

Fig. 112.

A *Resistance Box* is shown in Fig. 112 and its construction is explained by Fig. 113. In this particular resistance box the plug has been removed from the 20-ohm gap, so that when the box is connected by its terminals (on the left) in series in the circuit current passes through an insulated coil of manganin or constantin wire of exactly 20 ohms resistance. It is evident, in Fig. 113, that as a plug bridges the gap between *A* and *B*, but not between *B* and *C*, that the resistance of the right-hand coil only is in circuit.

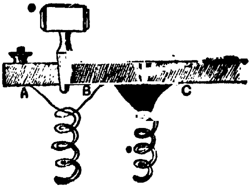

Fig. 113.

In Fig. 112 the gaps correspond to resistances of 500, 200, 100, 100, 50, 20, 10, 10, 5, 2, 2, 1 ohms; thus any resistance from 1 to 1000 ohms may be obtained.

Resistance in Series. The student may now summarize the results of his practical experience by aid of a diagram (Fig. 114)

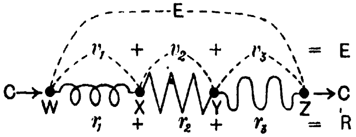

Fig. 114.

in which points *WXYZ* are joined by (say) 3 conductors, so that:

(*a*) the same current (*C*) passes through the 3 (say) resistances r_1, r_2, r_3 arranged in series;

(*b*) the total fall of potential between *W* and *Z* [= (say) *E*] is made up of the sum of the potential differences v_1, v_2 etc. as each resistance is added to the circuit;

(*c*) hence, the total resistance of the circuit $(R) = r_1 + r_2 + r_3$ etc.

Thus $$C = \frac{v_1}{r_1} = \frac{v_2}{r_2} = \frac{v_3}{r_3} \text{ etc.,}$$

but $$C = \frac{E}{R},$$

and $$E = v_1 + v_2 + v_3 \text{ etc. } [\S\ 67]$$

$$\therefore RC = r_1C + r_2C + r_3C \text{ etc.}$$

$$\therefore \mathbf{R = r_1 + r_2 + r_3 \text{ etc.}}$$

70. Resistance in Parallel.

The *conductivity* of a conductor is inversely proportional to its resistance (*R*): this quantity is called its **Conductance** and equals $\frac{1}{R}$.

If we join points W and Z, between which the P.D. is E, by the conductors in *parallel* as shown in Fig. 115, we should expect the *total conductance* $\left(\frac{1}{R}\right)$ to equal the *sum* of the *several conductances* $\frac{1}{r_1}, \frac{1}{r_2}, \frac{1}{r_3}$ etc.

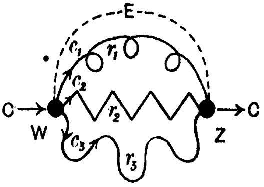

Fig. 115.

Let c_1, c_2, c_3 represent the currents in each wire and r_1, r_2, r_3 represent the corresponding resistances, then the **total current**

$$C = c_1 + c_2 + c_3 \text{ etc.}$$

but

$$c_1 = \frac{E}{r_1}; \; c_2 = \frac{E}{r_2}; \; c_3 = \frac{E}{r_3}.$$

$$\therefore C = E\left(\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} \text{ etc.}\right),$$

but

$$C = \frac{E}{R},$$

$$\therefore \mathbf{\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3}} \textbf{ etc.},$$

i.e. the total conductance = sum of conductance of the conductors.

71. Shunts.

It is often necessary to send only a fraction of the current through a sensitive instrument[1] or a particular part of the circuit: this may be accomplished by means of a **shunt.** For instance supposing you wished to measure a current (C) of several ampères flowing in a circuit and you were supplied with a milliammeter, *i.e.* one which measures only $\frac{1}{1000}$ ths of an ampère, what loop line or *shunt* of resistance S could you place between the terminals (A, B) of the milliammeter

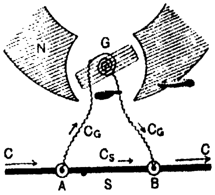

Fig. 116.

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[1] **Especially the moving-coil type of galvanometer.**

of resistance (A, B) that only $\frac{1}{1000}$ of the main current went through the instrument (Fig. 116)? The current (C) divides at A so that

$$\frac{1}{1000}C \text{ goes through the Galvanometer} = C_G,$$

$$\text{and } \therefore \frac{999}{1000}C \quad \text{,,} \quad \text{,,} \quad \text{Shunt} \quad = C_S.$$

Let E be the P.D. between A and B, and G and S the *resistances* of Galvanometer and Shunt respectively.

Then $$C_G = \frac{E}{G} \text{ and } C_S = \frac{E}{S}.$$

$$\therefore \frac{1}{1000}C = \frac{E}{G} \text{ and } \frac{999}{1000}C = \frac{E}{S}.$$

$$\therefore \frac{G}{S} = \frac{999}{1}.$$

$\therefore S = \frac{G}{999}$ if $\frac{1}{1000}$ part of C is to pass through the Galvanometer and similarly the resistance of the Shunt

$= \frac{G}{99}$ if $\frac{1}{100}$ part of C is to pass through the Galvanometer

$= \frac{G}{9}$ if $\frac{1}{10}$,, ,, ,, ,,

72. To find the internal Resistance (r) of a Cell (say a Daniell's Cell).

(1) Indirect Method.

Connect, in Series, 3 Daniell Cells each of internal resistance r, a tangent Galvanometer of known resistance (G) and a Resistance Box (R), then the *total resistance* of the circuit $\mathbf{R} = 3r + G + R$. If E = E.M.F. of the battery and C = the current, then

$$C = \frac{E}{\mathbf{R}} = \frac{E}{3r + G + R}.$$

Let θ = angle of deflection of the Galvanometer,

then $$C = k \tan\theta \quad \text{and} \quad k \tan\theta \times \mathbf{R} = E.$$

E may be taken as constant if the circuit is only completed for a *short* time for each observation of θ.

$$\mathbf{R} \propto \frac{1}{\tan\theta}.$$

Hence, varying the total resistance (R) by means of the resistance box (R), take 3 or 4 sets of observations of R and the corresponding θ[1]. Plot the

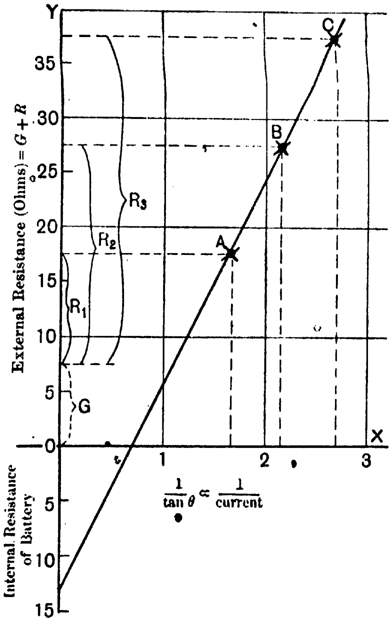

Fig. 117.

curve as shown in Fig. 117 according to the following observations, taking one division on the axis of Y as representing one ohm's resistance.

It is seen that the three points A, B and C obtained are in a straight line which, produced in the direction CA, cuts the axis of Y 13 divisions below 0 which represents on the same scale the internal resistance of the battery $= 3r$.

---

[1] A commutator should be included in the circuit and the mean of 4 galvanometer readings taken for each observation.

$$\therefore\ \mathbf{r} = \tfrac{13}{3} = \mathbf{4{\cdot}33\ ohms.}$$

	Resistance of Galvanometer G	Resistance Box R	External Resistance $= G + R + 3r$	Mean Deflection (θ)	$\tan\theta$	$\dfrac{1}{\tan\theta}$
a	7·5 ohms	10 ohms	$17{\cdot}5 + 3r$ ohms	31°	·601	1·66
b		20 ,,	$27{\cdot}5 + 3r$,,	25°	·465	2·15
c		30 ,,	$37{\cdot}5 + 3r$,,	20·5°	·371	2·70

(ii) **Indirect Method** by *voltmeter* and *ammeter* [see § 69, Exp. (ii)]; find r by the equation $C = \dfrac{E}{G + R + r}$, when the resistances of G and R are known.

(iii) **By Voltmeter** [see § 66, Exp. (iv)].

Find $E =$ E.M.F. of battery by voltmeter direct (Fig. 103 *a*).

$V_1 =$ P.D. between A and B (Fig. 103 *b*).

$V_1 = 50C$ where $C =$ current in AB.

But $C = \dfrac{E}{50 + r}$ where r is internal resistance of battery.

Hence $V_1 = \dfrac{50E}{50 + r}$. Since V_1 and E are known r can easily be obtained.

Grouping of Cells.

We can now write down Ohm's equation $C = \dfrac{E}{R}$ as applied to a battery of **n cells** each of **internal resistance r** and E.M.F. $= E$, and the total external resistance $= R$.

Cells in **Series** $\qquad C = \dfrac{nE}{R + nr}$,

Cells in **Parallel** $\qquad C = \dfrac{E}{R + \dfrac{r}{n}}$,

If there are n cells in *series* and m in *parallel*, *i.e.* a total of mn cells

$$C = \frac{nE}{R + \dfrac{nr}{m}}.$$

To obtain the **maximum** current it is found that in grouping a battery of cells *R* should as nearly as possible equal $\frac{nr}{m}$; *i.e.* the external and internal resistance should, as nearly as possible, equal each other.

73. Wheatstone's Bridge.

The simplest form of Wheatstone's Bridge consists of a high-resistance wire *D* (Fig. 118), the *bridge wire* of *uniform* thickness, stretched tightly along a scale, usually one metre in length, between two strips of copper, *A* and *C*, which together with a third strip *B* are furnished with binding-screws as indicated, and screwed to a board. These three strips are of negligible resistance. It is evident that there are two gaps in which certain resistances (R_1, R_2) may be inserted. A Leclanché or a Daniell's cell is connected between *A* and *C* and the circuit completed by a key *K*. If we trace the current *C* from *E* round the circuit we find that it divides at *A* and travels, (1) c_1 by way of the strip *B* and, (2) c_2 by the wire *D*, to *C* where it passes by the key, *K*, to the cell *E* again. By either route the potential falls between *A* and *C*, and *we can find a point D in the wire where the potential is the same as in the strip B*: this point is found by joining *B* through a galvanoscope (current detector) *G* to a wire which can be moved[1] along the bridge wire until no deflection occurs on making or breaking contact at *D*.

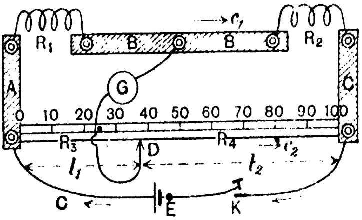

Fig. 118.

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[1] In some forms of Wheatstone's Bridge the "moving or travelling Contact" is made by means of a tapper.

Let R_3 = resistance of the piece of bridge wire AD, of length l_1,
R_4 = ,, ,, ,, DC ,, l_2.

Then since the potential in B is the same as at D

$$C_1R_1 = C_2R_3$$

and

$$C_1R_2 = C_2R_4.$$

$$\therefore \frac{R_1}{R_2} = \frac{R_3}{R_4} = \frac{l_1}{l_2}.$$

Exp. i. To find the resistance (R_2) of a piece of wire.

A piece of *Iron* wire No. 34 S.W.G. *length* 68 cms. was placed in the gap R_2 (Fig. 118); a *known* standard resistance (R_1) = **1 ohm** was placed in the gap R_1. A Daniell's cell was connected, in the position E, between A and C, and one terminal of a mirror galvanometer G [§ 44] was joined to B and the other to the moving contact D. (1) D was placed opposite the 10th scale division, and on tapping K the deflection of the spot of light (G) was to the *left*: (2) D was placed opposite the 90th scale division—the spot moved to the *right*, hence the neutral or "**null**" position of D lay between the 10th and 90th scale division and was ultimately found to be at **37·5**.

The length $AD = 37{\cdot}5 = l_1 \propto R_3$ when no deflection in G.

$\therefore$,, ,, $DC = 62{\cdot}5 = l_2 \propto R_4$,, ,,

Then since $R_1 = 1$ ohm and $R_1/R_2 = R_3/R_4$,

$$\frac{1 \text{ ohm}}{R_2} = \frac{37{\cdot}5}{62{\cdot}5}.$$

$$\therefore \mathbf{R_2 = 1{\cdot}66 \text{ ohms}}.$$

Exp. ii. To show that the resistance of a piece of wire depends upon

(a) the substance of which it is made and

(b) is directly proportional to its length (l), and

(c) inversely proportional to its cross-section (a).

Using the metre bridge (Fig. 118) and a 1-ohm or 2-ohm standard resistance in the position R_1, find the resistance, R_2, of the following wires and tabulate your results, thus:

Substance	S.W.G.[1]	length[1]	cross (sq. cms.) section (a)	$l_1 \propto R_3$	$l_2 \propto R_4$	R_1	$R_2 = X$ by cal.
(1) Copper	No. 36	100 cms.	·0002927	64 cms.	36 cms.	1 ohm	0·56 ohm
(2) Platinoid[2]	,, 28	30 ,,	·0011110	53 ,,	47 ,,	,,	0·88 ,,
(3) ,,	,, 28	15 ,,	·0011110	68·5 ,,	31·5 ,,	,,	0·44 ,,
(4) ,,	,, 20	30 ,,	·006566	87 ,,	13 ,,	,,	0·15 ,,
(5) Iron	,, 36	100 ,,	·0002927	38 ,,	62 ,,	2 ohms	3·25 ohms

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[1] Convenient lengths and gauges have been given. [2] Or other alloy of high resistance.

Deductions:

(*a*) from results of (5) and (1)

$$\frac{\text{Resistance of Iron}}{\text{Resistance of Copper}} = \frac{3{\cdot}25}{0{\cdot}56} = 6 \text{ approx.};$$

(*b*) from results of (2) and (3)

$$\frac{\text{Resistance of 30 cms. of wire}}{\text{Resistance of 15 cms. of same wire}} = \frac{0{\cdot}88}{0{\cdot}44} = \frac{2}{1};$$

(*c*) from results of (2) and (4)

$$\frac{\text{Resistance of wire of cross-section at area }{\cdot}001111}{\text{Resistance of wire of cross-section at area }{\cdot}006566} = \frac{0{\cdot}88}{0{\cdot}15} = \frac{6}{1} \text{ approx.}$$

$$\frac{\text{Area of cross-section No. 28 S.W.G.}}{\text{Area of cross-section No. 20 S.W.G.}} = \frac{{\cdot}001111}{{\cdot}006566} = \frac{1}{6} \text{ approx.}$$

Compare these results severally with the object of the exp.

Hence $\mathbf{R} = \mathbf{S}\dfrac{\mathbf{l}}{\mathbf{a}}$, where $\mathbf{l}$ = length of wire, $\mathbf{a}$ = its cross-sectional area and $\mathbf{S}$ depends on the particular material of the wire: and $\mathbf{S}$ is called the **Specific Resistance** [§ 75].

74. The Post Office Box.

A diagram of the arrangement of resistances in Wheatstone's Bridge is shown in Fig. 119. The arrangement in the Post Office Pattern of the Bridge is shown diagrammatically in Fig. 120 and a drawing of an actual **Post**

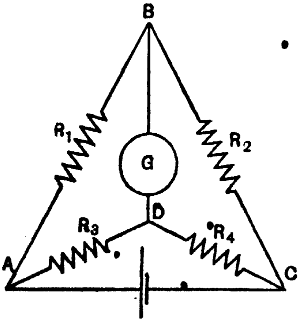

Fig. 119.

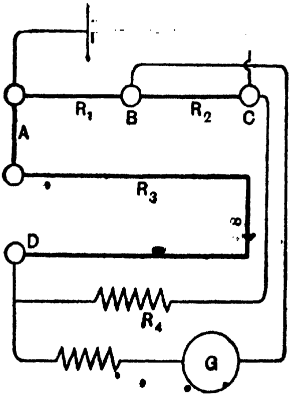

Fig. 120.

Office Box is given in Fig. 121. The student should make a plan of the particular box that he uses.

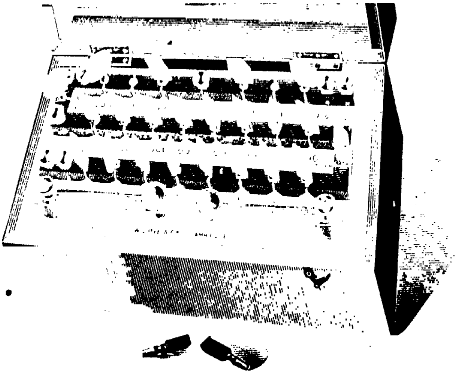

Fig. 121.

Note the order—A, 1000, 100, 10, B, 10, 100, 1000, C, in the arms corresponding to R_1 and R_2. If *equal* resistance gaps are opened by removing plugs in AB and BC, then the Resistance in R_3, when the "null" condition is obtained, will be the actual Resistance of R_4, thus :

$$\frac{R_1}{R_2}=\frac{R_3}{R_4};\quad \frac{100}{100}=\frac{R_3}{R_4}.\quad \therefore\ R_3=R_4.$$

If the ratio of the arms R_1/R_2 is 10/1 or 100/1 a correspondingly higher degree of accuracy is obtained in the ratio of the arms R_3/R_4.

R_3 is made up of 16 coils and plugs of resistances 1, 2, 2, 5, 10, 20, 20, 50, 100, 200, 200, 500, 1000, 2000, 2000, 5000 ohms which give a range from 1 to 11,000 ohms resistance.

Exp. To measure accurately the resistance of 100 cms. of Platinoid wire S.W.G. No. 28 by means of a P.O. Resistance Box.

Measure approx. 105 cms. of lacquer covered wire. Scrape off about 2 cms. of the insulating covering at one end and fix it on the binding screw C. Fig. 120. Measure off exactly 100 cms. and scrape the remainder of the wire and screw it accurately to D so that the 100 cms. of insulated wire are terminated at C and D. (1) Connect B and D to a Mirror Galvanometer ; (2) A and C to a Daniell's cell with a key in the circuit ; (3) remove the

∞ (Infinity) plug and depress the key: *Obs.* Deflection of spot of light to the *right*; (4) insert the ∞ plug and remove the 1 ohm plug and depress the key: *Obs.* Deflection is to *left*; ∴ the resistance R_4 is between 1 ohm and ∞. (This is a rough test that the connections are correct); (5) it was found that with three ohms resistance in R_3 the spot moved to the *right*, and with 2 ohms it moved to the *left*; ∴ R_4 is between 2 and 3 ohms; (6) extracted 100 ohms from AB and 10 ohms from BC, R_4 was found to lie between 29 and 30 ohms; (7) extracted 1000 ohms from AB and 10 ohms from BC, R_4 was found to be 292 ohms at the "null" condition.

$$\therefore \frac{1000 \text{ ohms}}{10 \text{ ohms}} = \frac{292 \text{ ohms}}{R_4 \text{ ohms}}. \quad \therefore \mathbf{R_3 = 2{\cdot}92 \text{ ohms.}}$$

75. Specific Resistance [$\mathfrak{S}$].

Referring to the formula $R = \mathfrak{S}\frac{l}{a}$ [§ 73, Exp. ii] we can find the value of $\mathfrak{S}$, the *Specific Resistance*, if we make $l = 1$ cm. and $a = 1$ sq. cm., *i.e.* we find the *Specific Resistance* of a material to be the *resistance of a cube of* 1 *cm. edge* to the passage of a stream of electrons moving parallel to one of its edges.

From the result of the last exp. **calculate the Specific Resistance of** that particular specimen of **Platinoid,**

$$\mathbf{R} = 2{\cdot}92 \text{ ohms}; \ \mathbf{l} = 100 \text{ cms.}; \ a = {\cdot}001111 \text{ sq. cms.}$$

for No. 28 s.w.g. wire. $\mathfrak{S}$ = Specific Resistance,

since $$R = \mathfrak{S}\frac{l}{a}, \quad \therefore 2{\cdot}92 \text{ ohms} = \mathfrak{S}\,\frac{100}{{\cdot}001111},$$

$$\therefore \mathfrak{S} = {\cdot}00003244 = 32{\cdot}44 \times 10^{-6} \text{ ohms.}$$

Exercise. From the results of Exp. ii, § 73, calculate the Specific Resistances of Iron and Silver.

76. Comparison of Resistances of Liquids.

The Resistances offered by various Liquids may be *compared* by the following device which is based on the Wheatstone's Bridge arrangement. The arms AB, BC (Fig. 122), contain 2 resistances (R_1, R_2) approximately equal, of about 30 ohms each[1]. The arm AD contains an electrolyte (say dilute salt solution) in a tube with copper terminals passed through corks as shown; its resistance R_3 need *not* be known. The electrolytes (say Copper Sulphate solution of various strengths) whose resistances are to be compared are placed in the tube in the arm *CD* in which an adjustable terminal *W* passes through the upper cork. It is necessary to eliminate the back E.M.F. at the terminals in the electrolytes. This is done by passing *alternating* currents through the liquids from the secondary coil *S* of an induction coil[1] from which the condenser has been removed from the primary circuit. The coil is inserted between *A* and *C* instead of a battery giving a continuous current. It is necessary to substitute a telephone receiver *T* for a galvanoscope between *B* and *D*. On depressing *K* the induction coil is actuated and a noise will also be heard in the telephone until the *null* condition is obtained by adjusting R_4, pushing in or withdrawing the wire *W*. When the buzzing in the telephone is reduced to a minimum, measure the *length L between the terminals* which *gives a measure of* R_4. Repeat the exp. substituting other solutions of various strengths in *W*, but keeping R_3 constant.

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[1] Two low resistance glow lamps for instance.

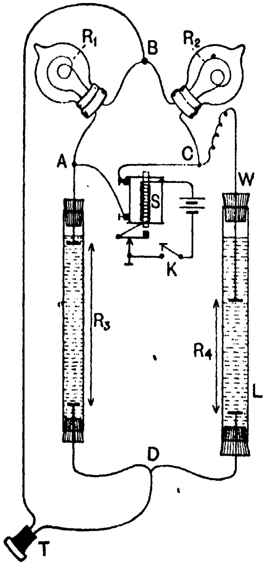

Fig. 122. *S* = Induction Coil.
T = Telephone.
W = Tube with adjustable Wire.

Practical Exercise. Find how the resistance of a solution of Copper Sulphate (say) varies with the concentration. Plot a curve from your results. (*Resistance* varies as *L*; *concentration* should be given in grams per litre.)

---

[1] Avoid shocks by not adjusting *W* when *K* is depressed.

Specific Resistance of a Liquid may be found by the above method, using a P. O. Box and a single tube W containing the solution (R_4). The area (a) of the terminals in the tube W must be known; they should be equal and circular of radius r cms. Then

$$R_4 = \mathbf{S}\frac{l}{a} = \mathbf{S}\frac{l}{\pi r^2}.$$

$$\therefore\ \mathbf{S} = \frac{R\pi r^2}{l}.$$

77. Resistance varies with the Change of Temperature of the Conductor.

The *resistance* of *pure metals increases as the temperature rises.* This may be shown by inserting in a Wheatstone's Bridge (R_2) a spiral of thin lacquer-covered[1] iron wire contained in a vessel of water (Fig. 123) which may be first cooled to 0° C. by adding ice and afterwards gradually raised to a temperature of about 80°. A *thermometer T* and a glass *stirring rod S* are necessary accessories. Thick copper wires, insulated with lacquer, connect the spiral to the bridge terminals B and C. Resistances are measured at intervals of 10° from 0° to 80° C. ($= R_0 \ldots R_{80}$) and a graph plotted which is found to be almost a *straight line.* Continue the curve to find the resistance at 100° $= R_{100}$.

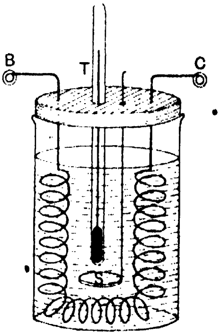

Fig. 123.

Then $R_{100} - R_0 =$ rise in resistance R_0 coil for 100° C.

$$\therefore\ \frac{R_{100} - R_0}{100\,R_0} = \text{ ,, a resistance of 1 ohm coil for } 1^\circ\text{ C.}$$

$$\therefore\ \frac{R_{100} - R_0}{R_0} = \text{ ,, ,, ,, 100 ohm coil for } 1^\circ\text{ C.}$$

$$= \text{percentage increase in resistance per } 1^\circ\text{ C.}$$

$$= 0{\cdot}4\ \%\text{ for pure metals (approx.).}$$

---

[1] Uninsulated wire may be used if the coil is immersed in paraffin oil in an inner vessel, surrounded by an outer water bath, the temperature of which may be raised.

If t represents the rise in temperature above 0° then

$$\frac{R_t - R_0}{t \, . R_0} = \textbf{Temperature Coefficient of Resistance} = \rho,$$

i.e. ρ = Resistance increment of one ohm coil per degree.

$$\therefore \; R_t = R_0 (1 + \rho t).$$

Dewar and Fleming found that at very low temperatures the resistance was so much reduced that at −273° C. (the absolute zero) pure metals would offer no resistance to the passage of electrons.

The Resistance of *Constantin or Eureka* (an alloy of 40 °/$_o$ Ni and 60 °/$_o$ Cu) and *Manganin* (Mn 4, Ni 12, Cu 84) wires is not affected by change of temperature.

The chief exception to the general rule is carbon, the resistance of which *decreases* greatly as its temperature rises.

Electrical Resistance Thermometers (Pyrometers).

The principle that resistance increases with rise in temperature is applied in making high temperature thermometers (pyrometers). A fine platinum spiral, of known resistance at ordinary temperatures, is contained in a porcelain tube which is placed in the furnace or crucible the temperature of which is required. The resistance of the coil is then measured while it is in the furnace. The coefficient of increase of resistance (ρ) being known the rise in temperature is calculated from the formula $R_t = R_0 (1 + \rho t)$.

78. Typical Examples, with their Solutions, on Chap. VII.

Example i. An electric circuit consisting of a battery, tangent galvanometer and resistance box is traversed by a current which gives a deflection of 40° when there is no resistance in the box and 15° when the box contains 10 ohms. What is the remaining resistance in the circuit?

Let R = remaining resistance in ohms; E = E.M.F. of battery and C_1 and C_2 the currents through the galvanometer.

$$C_1 = K \tan 40^\circ = \frac{E}{R} \quad \ldots\ldots\ldots\ldots (a),$$

$$C_2 = K \tan 15^\circ = \frac{E}{10+R} \quad \ldots\ldots\ldots\ldots (b).$$

Hence since $\tan 40^\circ = {\cdot}8391$,

$$\tan 15^\circ = {\cdot}2679, \quad \therefore \frac{8391}{2679} = \frac{10+R}{R}.$$

$$\therefore R = 4{\cdot}6 \text{ ohms (approx.)}.$$

Example ii. The total current from a main supply of 110 volts sent through a lighting circuit containing 20 lamps in parallel is 10 ampères. Find the resistance of each lamp.

Let R = equivalent resistance of lamps in ohms.

R_1 = resistance of each lamp.

Then $R = \frac{R_1}{20}$, since lamps are in parallel [§ 70].

$$C = \frac{E}{R}. \quad \therefore 10R = 110.$$

$$\therefore R = 11 \text{ and } R_1 = 11 \times 20 = 220 \text{ ohms.}$$

Example iii. A total current of 6 ampères flows through three wires in parallel whose resistances are 2, 3, 4 ohms respectively. Calculate the current in each wire.

Let R = equivalent resistance; E = potential difference between the ends, and C_1, C_2, C_3 the currents in each wire.

$$C_1 = \frac{E}{2}, \quad C_2 = \frac{E}{3}, \quad C_3 = \frac{E}{4}.$$

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{3} + \frac{1}{4} = \frac{13}{12}. \quad \therefore R = \frac{12}{13} \text{ ohm.}$$

Now $C = \frac{E}{R}$. $\therefore 6 = \frac{E}{\frac{12}{13}}$. $\therefore E = \frac{6 \times 12}{13}$ volts.

Hence $C_1 = \frac{6 \,.\, 12}{2 \,.\, 13} = 2\frac{10}{13}$ amps. $C_2 = 1\frac{11}{13}$ amps. $C_3 = 1\frac{5}{13}$ amps.

Example iv. The terminals of a battery consisting of 3 cells in series each having an E.M.F. of 1·6 volts, and a resistance of 1 ohm, are joined by two wires in parallel, one of 4 ohms, the other of 5 ohms. Calculate the current in each wire. Let R = equivalent resistance of wires.

$$\therefore \frac{1}{R} = \frac{1}{5} + \frac{1}{4} = \frac{9}{20}. \quad \therefore R = 2\frac{2}{9} \text{ ohms.}$$

If C = total current in ampères, then $C = \frac{4 \cdot 8}{R + 3} = \frac{4 \cdot 8}{5\frac{2}{9}} = \frac{48 \times 9}{470}$ amps.

Let C_1 = current in wire of 5 ohms, C_2 = current in wire of 4 ohms.

Hence $$C_1 = \frac{4}{9} \times \frac{48 \times 9}{470} = \frac{192}{470} = \cdot 4 \text{ amp. (approx.).}$$

$$C_2 = \frac{5}{9} \times \frac{48 \times 9}{470} = \cdot 51 \text{ amp. (approx.).}$$

Example v. The specific resistance of Eureka wire = ·000048 ohm. Find the length of Eureka wire No. 30, diameter ·315 mm. required for a resistance of 10 ohms.

$$\text{Specific resistance} = \frac{\text{total resistance} \times \text{area of section}}{\text{length}},$$

$$\therefore \text{length} = \frac{10 \times \frac{22}{7} \times \left(\frac{\cdot 0315}{2}\right)^2}{\cdot 000048} = 162 \text{ cms.}$$

QUESTIONS ON CHAPTER VII

1. In any simple electrical circuit what relation exists between the strength of the current, the E.M.F. of the battery circuit and the resistance of the circuit? How would you verify the relationship experimentally? Define the practical units of current, E.M.F. and resistance.

2. If the resistance between the terminals of a battery is doubled, is there any alteration caused in (*a*) the strength of the current, (*b*) the E.M.F. of the battery? If so, to what extent?

3. What exactly is meant by the E.M.F. of a cell? Describe a method of quickly determining its value. Account for the falling off of the potential difference between the terminals when the current through the circuit is increased by lowering the external resistance.

4. Describe a simple form of voltmeter and contrast it with the ammeter. How is it possible to fit up a tangent galvanometer for use as a voltmeter?

5. An unmarked instrument for measuring electric current is handed to you. What characteristics would you look for to determine whether it had been designed as (*a*) an ammeter, (*b*) a voltmeter, or (*c*) an instrument obeying the tangent law? What is the relation of the ampère and the volt to the absolute units of electricity?

6. Describe any simple experimental method of comparing the E.M.F.'s of two given cells. On what principles does your method depend?

7. Show, with simple diagrams, how resistances can be connected (*a*) in series, (*b*) in parallel, and deduce appropriate formulae for the equivalent resistances of the systems.

8. Repeat Q. 7 for cells. What is meant by the internal resistance of a cell? How would you quickly determine the internal resistance of a given Daniell's cell? How is the internal resistance of a simple cell altered by varying (*a*) the area of the plates, (*b*) their distance apart, (*c*) the strength of the electrolyte?

9. The P.D. of a city supply is 220 volts. Construct a graph showing the variation in the total current passing through a switchboard due to the insertion of successive lamps each of resistance 300 ohms (*a*) in parallel, (*b*) in series. (See Appendix I.)

10. What is a shunt? Describe its use in connection with an ammeter.

11. A galvanometer of 100 ohms resistance can only indicate a maximum current of 5 ampères. What must be the value of the shunt, used in conjunction with this instrument, to record currents up to 100 amps.?

12. It is desired to use an ammeter reading up to one ampère and having a resistance of 1·5 ohms for measuring currents up to 10 amps. Explain carefully, giving all the calculations necessary, what would need to be done to attain this end. L.U. 1920.

13. A battery whose E.M.F. is 1·2 volts and internal resistance 1 ohm is connected in series with a coil of resistance 5 ohms and a galvanometer of resistance 10 ohms. What is the current through the galvanometer? What will be the effect of replacing the battery by two similar cells (*a*) in series, (*b*) in parallel?

14. A Daniell's cell of E.M.F. 1·1 volts and ½ ohm internal resistance is connected in series with a tangent galvanometer of resistance 2 ohms. Compare the current passed through the galvanometer with that from a Leclanché cell E.M.F. 1·35 volts, internal resistance ·25 ohm.

15. Under what conditions are cells used (*a*) in parallel, (*b*) in series?

Four Daniell's cells of E.M.F. 1·1 volts and internal resistance ·5 ohm are connected (*a*) in series, (*b*) in parallel through an external resistance of ·2 ohm. Compare the currents produced in each case.

If the external resistance is increased to 20 ohms, deduce the new values for the currents produced. State your conclusions.

16. Find the resistance of the wire which must be joined in parallel with a wire of 15 ohms resistance to reduce their combined resistance to 13·5 ohms.

17. The terminals of a battery consisting of three cells in series, each having an E.M.F. of 1 volt and a resistance of 1 ohm, are joined by two wires in series, one of 4 ohms and the other of 5 ohms. Give the intensity (value) of the current which will pass through the battery. O.L.S. 1920.

18. Two coils have a combined resistance of 12 ohms when connected in series, and 1⅔ ohms when connected in parallel. Find their respective resistances. L.M. 1917.

19. The terminals of a battery are connected by a voltmeter which shows a reading of 15 volts. The terminals are then also joined by wires to an ammeter. The ammeter registers 1·5 ampères and the voltmeter 9 volts.

(*a*) Explain drop in voltmeter reading.

(*b*) Calculate the resistance of the battery.

(*c*) Find the resistance of the ammeter with its leads. O.L.S. 1920.

20. The Specific Resistance of Platinoid wire is about ·000034 ohm. Find the length of wire No. 26, diam. = ·457 mm. required for a resistance of 100 ohms.

21. Write a careful description of a resistance box. How are the coils made and wound?

22. Give full details of any experiment you would perform to obtain the resistance of a given coil of wire using an ammeter and a voltmeter.

23. How can the resistance of an electric lamp be measured? Draw a diagram indicating the apparatus that would be used and the manner in which it would be connected up. L.U. 1920.

24. Describe the method of obtaining the value of an unknown resistance by what is known as the Wheatstone Bridge. Prove any formula you use.

25. You are required to make a 1 ohm coil from a piece of platinoid wire. Give the details of the experiment, carefully stating what precautions are necessary to ensure accuracy.

26. In the Wheatstone's Bridge method explain why

(i) the final bridge reading should not be near the ends of the bridge,

(ii) it is advisable to interchange the positions of the unknown resistance and the resistance box,

(iii) the diameter of the bridge wire should be uniform. O.L.S. 1920.

27. What is a Post Office Box? Describe its construction and state how it is used in the accurate determination of unknown resistances.

28. Describe the Potentiometer method of comparing the E.M.F. of two cells. State why

(*a*) the potentiometer wire should be of uniform section and as long as possible with convenience,

(*b*) an accumulator is usually used to provide the main current.

29. Describe an accurate method of obtaining the value of the internal resistance of a cell. Why do the values obtained for a given make of cell vary widely in practice?

CHAPTER VIII

UNITS AND DEFINITIONS.
HEATING EFFECTS OF THE ELECTRIC CURRENT

70. I. **Absolute Units** (A-).

The absolute unit of electrical charge (or quantity), denoted by **q.**

If two *like* charges of electricity of equal strength, placed 1 cm. apart, repel each other with a force of 1 dyne, each is called an *absolute unit of charge.*

The absolute unit of Potential Difference (or of E.M.F.), denoted by **e.**

If 1 *erg* of work is needed to move 1 abs. unit of charge or quantity, from one point to another, against the force of an electric field there is said to be an unit of *Potential Difference* between the two points.

The absolute electro-magnetic (A.-E.-M.) unit of Current was defined in § 46 and is denoted by **c.**

The A.-E.-M.-unit of Resistance, denoted by **r.**

A wire or other conductor has the A.-E.-M.-unit of Resistance when an absolute unit of P.D. must be maintained between its ends in order that the A.-E.-M.-unit of current may flow in the wire.

The A.-E.-M.-unit of Quantity of electricity, denoted by **q,** is conveyed by the A.-E.-M.-unit of current in 1 sec.

II. **Practical Units** (P-).

The Practical unit of Potential Difference (or of E.M.F.) [the **Volt**].

The E.M.F. of a Voltaic Cell, *i.e.* the P.D.[1] between the terminals on "*open circuit,*" is more than 100,000,000 absolute units of P.D.

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[1] For distinction between E.M.F. and P.D. see pp. 17–21.

These units are evidently very small and it is therefore necessary for practical purposes to increase the unit considerably. The unit selected is called the *Volt*.

1 Volt = 10^8 A.-E.-M.-units of P.D.

E expresses the E.M.F. or P.D. in Volts.

The P-unit of Current [the Ampère] has already been defined [§§ 45–61].

1 Ampère = $\frac{1}{10}$ (*or* 10^{-1}) A.-E.-M.-unit of Current.

C expresses the current in Ampères.

The P-unit of Resistance [the Ohm].

The value of the Ohm follows from the equation which expresses Ohm's Law, viz.

$$\frac{\text{E.M.F.}}{\text{current}} = \text{Resistance},$$

$$\textit{i.e.}\quad \frac{\text{Volts}}{\text{Ampères}} = \text{Ohms (practical units)},$$

$$\textit{i.e.}\quad \frac{10^8\ \text{A.-E.-M.-units of E.M.F.}}{10^{-1}\ \text{A.-E.-M.-units of current}} = 10^9\ \text{A.-E.-M.-units of Resistance},$$

∴ 1 Ohm = 10^9 A.-E.-M.-units of Resistance.

R expresses the Resistance in Ohms.

The P-unit of Quantity (the Coulomb) is carried by 1 Ampère in 1 sec.

Q expresses the Quantity in Coulombs $= Ct$,

i.e. Q coulombs are carried by C ampère in t secs.

1 Coulomb = $\frac{1}{10}$ (*i.e.* 10^{-1}) A.-E.-M.-unit of Quantity.

80. Electrical Work, Energy, Power.

Work. From the definition given in § 79 of the absolute unit of P.D. 1 erg of work is done when an absolute unit quantity of electricity is moved from one point to another between which there is an absolute unit of P.D.

When **q** units are moved through a P.D. of **e** units **qe** ergs of work are done = **w**,

$$i.e.\ \mathbf{w} = \mathbf{qe} \text{ in absolute units.}$$

The **Joule.** If the P-unit of quantity, 1 *coulomb* (*i.e.* 10^{-1} A-units), is moved through a P.D. of 1 *Volt* (*i.e.* 10^8 A-units) the **work done** is called a **Joule;** but,

$$\mathbf{w} = \mathbf{q} \times \mathbf{e},$$

$\therefore$ the *P*-unit of Work $= 10^{-1} \times 10^8 = 10^7$ ergs (A-units)

$= 1$ coulomb $\times$ 1 Volt $=$ 1 Joule (P-units).

$\therefore$ **1 Joule = 10^7 ergs.**

Hence **work** done (W) when Q coulombs are moved through a P.D. of E volts $= QE$ joules,

i.e. $W = QE$ joules, ...(1),

but 1 coulomb = quantity carried by 1 ampère in 1 sec.

$\therefore Q = Ct =$,, C ,, t ...(2).

Substituting (2) in (1),

$W = CtE$ joules ....(3),

i.e. $\mathbf{w} = CtE \times 10^7$ ergs ....(4),

Energy is the capacity to do work.

Power is the **rate** of doing work.

If W ergs of work are done in a circuit in t secs. then rate of doing work, *i.e.* *power* $= \dfrac{W}{t}$ units of electrical power, but by equations (1) and (3),

$$W = QE \text{ joules} = CEt \text{ joules},$$

$$\therefore \frac{W}{t} = CE \text{ joules per sec. } \ldots\ldots\ldots\ldots\ldots\ldots(5).$$

---

[1] 1 Joule = ¾ of a Foot-Pound (approx.). *Work done* is expressed here by **w** ergs or *W* joules.

So that the *Power* at which an electric current does work is equivalent to the product of the current (in *ampères*) and the pressure (in *volts*) under which it is driven through the circuit.

Power = amps. × volts.

Electrical power is expressed in units called **Watts.**,

∴ by equation (5) **1 Watt = 1 Joule per sec.**

= the power developed by a current of 1 Ampère driven by an electric pressure of 1 Volt,

hence **watts = ampères × volts.**

A **Kilowatt** is 1000 Watts.

To convert Watts into Horse-Power (H.-P.).

1 H.-P. = 33000 ft.-pounds per minute
= 550 ,, ,, sec.
[1 ft. = 30·48 cms., 1 pound = 453·6 grams, $g = 981$.]
= 550 × 453·6 × 981 × 30·48 ergs per sec.
= 746×10^7 ergs per sec. (approx.)
= 746 joules per sec.
= **746 watts**
= $\frac{3}{4}$ kilowatt (approx.).
∴ **1 kilowatt = $1\frac{1}{3}$ H.-P.** (,,).

A **Board of Trade Unit** (B.T. unit) is a *Kilowatt* of energy kept going for 1 *hour* = **1 kilowatt-hour**, hence **B.T. units = Kilowatts × Hours.**

[For worked Examples see § 85.]

81. Heating Effect of the Electric Current.

I. The Joule Effect.

The reader's attention was drawn in the first paragraph of this book to the distribution and dissipation of the electric energy of a current. Along a single street, for instance, the supply of electric energy conveyed by the town mains is utilized for lighting the streets and houses, for working the motors on the trams and in the workshops, for electroplating, for welding metals, for heating, cooking and ironing, for X-ray work and cauterizing at the hospitals and in many other ways. The conversion of electric energy into heat energy is called the Joule effect.

Exp. (i). To illustrate the conversion of electric energy to heat energy—The simplest method of dissipating electric energy—connect 3 or 4 Bichromate, or Grove's, or even dry-cells in series, and join the outer terminals by (say) an inch length of *fine iron wire*. The electric energy is dissipated in heat *throughout the circuit*, but is chiefly noticeable in the wire which becomes red hot and ultimately fuses.

The heating is due to the **resistance** of the conductor to the passage of electrons. In § 80 we found that a current of C ampères flowing for t secs. through a P.D. of E volts develops $Ct \,.\, E$ joules, *i.e.*

$$W = Ct \,.\, E \text{ joules} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1).$$

If the **resistance** of the conductor $= R$, we know by Ohm's Law that $E = CR$ volts.

Substituting in (1)

$$\begin{aligned} W &= Ct \,.\, CR \text{ joules} \\ &= C^2 \,.\, Rt \text{ joules,} \\ \mathbf{w} &= C^2 \,.\, Rt \times 10^7 \text{ ergs} \ldots\ldots\ldots\ldots\ldots(2). \end{aligned}$$

The Mechanical Equivalent of 1 Calorie of Heat was found[1] to be $4{\cdot}2 \times 10^7$ ergs (called $\mathbf{J}$). If the heat developed $= H$ calories, then

$$\begin{aligned} \mathbf{w} = JH &= C^2Rt \times 10^7 \text{ ergs} \ldots\ldots\ldots\ldots\ldots\ldots(3), \\ \therefore \mathbf{4{\cdot}2\,H} &= \mathbf{C^2Rt} \quad \ldots\ldots\ldots\ldots\ldots\ldots(4), \\ &= \mathbf{CtE} \quad \ldots\ldots\ldots\ldots\ldots\ldots(5), \end{aligned}$$

where H is in Calories, C in Ampères, R in Ohms, t in secs. and E in volts.

This equation expressed in words constitutes **Joule's Law**, viz. the number of *units of heat* developed in a conductor is *proportional to* (*a*) the *square of the current-strength*,

(*b*) the *resistance* of the conductor,

(*c*) the *time* that the current flows.

Exp. (ii). To show that $H \propto RT$ [see (*b*) and (*c*) above] the current remaining constant.

Take two small calorimeters M_1, M_2, of approx. the same weight and shape, each fitted with a spiral (see Fig. 123) of the same kind of thin lacquer-covered (*i.e.* insulated) manganin wire of measured lengths[1] l_1, l_2 *Call the resistance of the spirals* R_1, R_2, then

---

[1] See *Experimental Science*, Part I, Physics, Section IV, Heat, § 166.

$$R_1/R_2 = l_1/l_2.$$

Counterpoise the calorimeters and add to each exactly equal weights of water which, to reduce errors of radiation, should be cooled to a few degrees below the temp. of the laboratory at the beginning of the experiment. Adjust the thick insulated copper leading wires, shown in Fig. 124, to touch the water.

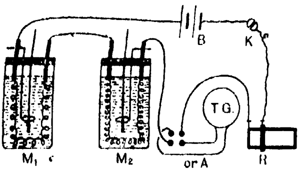

Fig. 124.

In order to pass the same current through both calorimeters connect them in series with a 4-volt accumulator (B), a tangent galvanometer (T.G.) with commutator (Fig. 124), *or* an ammeter (A) reading to 2 amps., a variable resistance (R) and a plug (K). Using a 0°—30° thermometer, reading to 0·2° C., take temperature readings (T_1, T_3, T_5 for M_1 and T_2, T_4, T_6 for M_2) at the beginning and the end of two consecutive intervals of t secs. (say 10 minutes each). Reverse the current quickly between the two intervals if a T.G. is used. By means of the adjustable resistance (R), keep the *current constant* throughout.

[For Exp. (iii), it is also necessary to take the 4 galvanometer readings, and obtain the mean (say) $\theta_1°$ *or* if an ammeter is used record the *current* (say) C_1.]

Then

	1st interval (t sec.)	2nd interval (t sec.)	Total time ($2t$)
(A) Rise in temp. of	$M_1 = T_3° - T_1°$	$T_5° - T_3°$	$T_5° - T_1°$
" " "	$M_2 = T_4° - T_2°$	$T_6° - T_4°$	$T_6° - T_2°$

It is found that for each equal interval and using equal weights of water

$$\text{(B)}\ \frac{\text{Rise in temp. of } M_1}{\text{Rise in temp. of } M_2} = \frac{l_1}{l_2} = \frac{R_1}{R_2},$$

so that by keeping C and t constant we have shown that the *H developed is proportional to the R*;

(C) also, Rise in Temperature (proportional to Heat developed) in either calorimeter is proportional to the time that the current flows,

$$e.g. \text{ for } M_1\ \frac{T_3 - T_1}{T_5 - T_1} = \frac{t \text{ sec.}}{2t \text{ sec.}} = \frac{1}{2}.$$

---

[1] If the 2 coils are not of the same wire and of unknown lengths, it is necessary to find the Resistance of each coil. A useful ratio of lengths is ½.

Exp. (iii). To show that $H \propto C^2$ [see Joule's Law (*a*)].

Cut out either of the Calorimeters (say) M_1 [use Fig. 124 with M_1 removed] and repeat Exp. (ii) with *exactly* the same weight of water in M_2. Let the Temperature readings be T_7°, T_8°, T_9° at the beginning and the end of two equal consecutive intervals of t secs. (say 10 minutes each). Let mean T.G. deflection $= \theta_2$ *or*, if an ammeter is used, keep the current constant at C_2, then it is found for any two corresponding intervals for M_2

$$\frac{\text{Rise in Temp. in Exp. (iii)}}{\text{Rise in Temp. in Exp. (ii)}} = (\text{say})\ \frac{T_9^\circ - T_7^\circ}{T_6^\circ - T_2^\circ} = \frac{\tan \theta_2^2}{\tan \theta_1^2} = \frac{C_2^2}{C_1^2}.$$

So that by passing different currents through the same quantity of water for equal times, each current remaining constant during each experiment, we have shown that the *Heat developed is proportional to the square of the current.*

82. To find the mechanical Equivalent of Heat [Joule's Equivalent J] by an Electrical method.

$JH = C^2Rt$. [See § 81, Equations (1)–(4).]

The method is identical with that of Exp. (iii), § 81 above, but it is necessary to know (1) the Resistance of the coil (**R**), (2) the weight of water and the water equivalent of the calorimeter in order to measure the heat developed (**H**), in addition to **C** by T.G. or ammeter and **t** by the clock [use Fig. 124 without M_1] = (say) 7·5 ohms.

(*a*) **To obtain R,** use a Wheatstone's Bridge.

(*b*) **To obtain H:**

(1) Weigh the empty copper calorimeter (S.H. = ·095)	20 gms.
(2) ,, ,, ,, ,, + water	70 ,,
∴ Wt. of cold water	50 ,,
add water equivalent of calorimeter (20 × ·095) = approx. ...	2 ,,
add water equivalent of thermometer	0·5 ,,
∴ Total water equivalent of calorimeter and contents	52·5 ,,
(3) Temperature *before* passing current	10° C.
,, of Laboratory[1] 15°.	
,, after passing current	20° C.
Rise in temperature of 52·5 gms. water	10° C.

∴ H = mass of water × rise of T. = 52·5 × 10 = 525 calories.

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[1] Note how *radiation error* is avoided. Do not start the current until the temp. of the cold water has risen to about 5° *below* the temp. of laboratory and continue until the temp. of water has risen 5° *above* lab. temp.

(*c*) **To obtain C** use a T.G. and commutator, reversing the current when the temp. has risen to that of laboratory (mean of 4 readings θ°); the constant (k) of the T.G. must be known :

Then current $= k \tan\theta =$ (say) 0·5 amp., *or* use an ammeter. In either case keep the current constant by means of the variable resistance R [see Fig. 124 without M_1].

(*d*) **To obtain t:** use watch with seconds-hand = (say) 19 mins. 40 secs. = 1180 secs.;

then substituting in Joule's equation $JH = C^2Rt$

$$J \times 525 = 0{\cdot}5 \times 0{\cdot}5 \times 7{\cdot}5 \times 1180.$$

$$\therefore \mathbf{J} = {\cdot}25 \times 7{\cdot}5 \times 1180/525 = \mathbf{4{\cdot}21}\ \textbf{Joules}\quad \text{[P-units]}$$

$$= \mathbf{4{\cdot}2} \times \mathbf{10^7}\ \textbf{ergs}\ \text{[A-units]}.$$

Practical Exercise. (*a*) Given the voltage of the local supply, suggest a method of finding (1) the *current* used by, and (2) the *resistance* of an electric glow lamp. Design the calorimeter you would use and name all *precautions* necessary for safely and successfully carrying out your exp. (*b*) Hence how would you calculate (3) the number of kilowatts used per hour, and (4) the cost per hour given the price of a B.T.U. [See Example ii, § 85.]

83. II. **The Seebeck Effect** was discovered by Seebeck in 1821. It may be illustrated by the following.

Exp. Two dissimilar metals, *e.g.* (*a*) *copper* and *iron*, or (*b*) *bismuth* and *antimony*, soldered or jointed together, have their free ends joined through a mirror galvanometer (Figs. 125 *a* and *b*). If the junction *H* is *warmed* to a temperature higher than the rest of the circuit, an E.M.F. is produced which drives a current across the junction in the order mentioned above and so round the circuit.

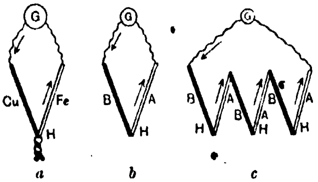

Fig. 125.

If, on the other hand, the junction is cooled below the rest of the circuit the current is reversed.

The effect is greatly enhanced if several couples are joined in series and corresponding junctions are warmed (Fig. 125 *c*).

84. III. The Peltier Effect.

In order to obtain the Seebeck Effect *heat* energy was supplied to or taken from a junction, where it was transformed to electric energy. The Peltier Effect is the converse of this.

If an E.M.F. is supplied to the circuits shown in Figs. 125 *a*, *b*, and *c*, so that the current flows in the *same* direction, the junctions are *cooled*, if in the *opposite* direction they are heated (Fig. 126).

It must be borne in mind that the Joule Effect will disturb the Peltier Effect, for the temperature of the metals will rise owing to their resistance to the current. The Joule Effect may, however, be eliminated from a demonstration exp. by passing current through two adjacent junctions (Fig. 127). (1) *B* to *A* on the left, and (2) *A* to *B*, cold (*C*) being developed at the first and heat (*H*) at the second by the Peltier Effect, while the Joule Effect will go on equally at both junctions. If these junctions are placed respectively in the bulbs of a differential air thermometer, only the Peltier Effect alters the position of the mercury index which therefore moves to the left.

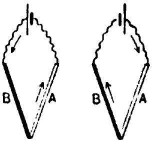

Fig. 126.

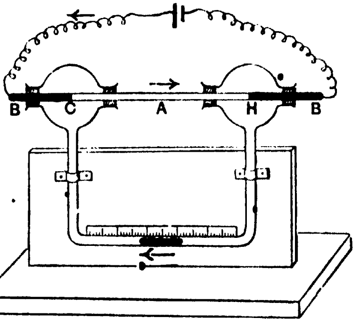

Fig. 127.

85. Typical Problems on Heating and Power.

Example i.

A current passes along a spiral of wire immersed in water contained in a calorimeter. Calculate the P.D. between its ends from the following data:

Wt. of calorimeter = 20·2 gms.
Water equivalent of calorimeter = 2 gms.
Wt. of calorimeter + water = 218·2 gms.
Current registered by ammeter = 2 ampères.
Temp. at beginning of experiment = 15°C.
Temp. after 15 minutes = 17°C.

Equiv. wt. of water = 200 gms. Heat developed in 15 mins. = 400 cals.

Now $$JH = ECt,$$

and when H is in cals., C in amps., E in volts, $J = 4{\cdot}2$. [See § 81.]

$$\therefore 4{\cdot}2 \times 400 = E \times 2 \times 15 \times 60.$$

$$\therefore \mathbf{E = {\cdot}93\ volt.}$$

Example ii.

A 40 watt lamp is connected to a 220 volt supply circuit. How much current will it take and how much will it cost to run for 20 hrs. at 8*d.* per Board of Trade unit?

Watts = amps. × volts. [§ 80.]

$$\therefore 40 = 220 \times C.$$

$$\therefore C = \tfrac{4}{22} = \tfrac{2}{11} \text{ ampère.}$$

1 Board of Trade unit = 1 kilowatt × 1 hr.

$$\text{No. of B.T.U. consumed} = \tfrac{40}{1000} \times 20 = \tfrac{8}{10} = {\cdot}8.$$

$$\therefore \text{Cost} = {\cdot}8 \times 8 = \mathbf{6{\cdot}4\ pence.}$$

Example iii.

An electric radiator which takes 1·5 kilowatts is connected to mains which supply electricity at 200 volts pressure. Calculate (i) the strength of the current passing through the radiator, (ii) the resistance of the radiator, (iii) the number of calories of heat produced in 1 hour.

(1 cal. = 4·2 Joules. 1 watt = 1 Joule per second.) O.L.S. 1920.

Watts = amps. × volts.

$$\therefore 1500 = C \times 200.$$

$\therefore C =$ **7·5 ampères** ....(i).

$$C = \frac{E}{R}. \quad \therefore 7{\cdot}5 = \frac{200}{R}.$$

$\therefore$ **R = 26·6 ohms** ....(ii).

1 watt = 1 Joule per sec.

1·5 K.W. = 1500 Joules per sec.

= 1500 × 60 × 60 Joules per hour

$$= \frac{1500 \times 60 \times 60}{4{\cdot}2} \text{ cals. per hour}$$

= **1285714 cals.**

QUESTIONS ON CHAPTER VIII

1. What is meant by the term "Mechanical Equivalent of Heat"?

In this connection, define the units calorie, erg and Joule.

Obtain a relation for the heat developed in a conductor carrying an electric current. Be careful to state the units in which you are working.

2. How would you proceed to discover experimentally the connection between the heat developed in a coil of wire and the current passing through it? Describe in detail the precautions you would take to ensure an accurate answer.

3. An electric current is passed along a chain composed of alternate links of platinum and silver. The platinum links glow brightly—why is this?

4. Two equally long copper and silver wires are suspended from two supports and are so connected that a current travelling along the copper wire returns along the silver. It is found that the copper wire sags. Give a reason for this.

The current is now caused to flow along both wires in parallel and the silver wire sags. Why is this?

5. Explain why heat is developed in the wire filament of a glow lamp whilst the leads are quite cool.

6. What is the function of the "fuse" inserted in an electric lighting or power circuit?

7. A light calorimeter contains 100 gms. of water at 10° C. A coil of G.S. wire is immersed in the water and a current of 1 ampère is passed through, the P.D. between the ends of the wire being 28 volts. Calculate the temperature at the end of 5 minutes.

8. A coil of wire of resistance 3 ohms is placed in a light calorimeter containing 400 gms. of water. Find the current required to raise its temperature 6 degrees per minute.

9. Calculate Joule's Equivalent from the following data:

Equiv. wt. of water = 100 gms.
Initial temp. = 15° C. Mean deflection of galvanometer = 25°.
Final temp. = 28° C. Reduction Factor of galvanometer for prac. units of current = 3·24.
Duration of exp. = 40 mins. Resistance of coil = 1 ohm

10. Define watt, kilowatt, horse-power. State the relation between the watt and 1 H.P. What H.P. will be required to maintain a 50 C.P. glow lamp taking 1½ watts per candle power? If the P.D. between its terminals is 236 volts, what is the current passing through the filament?

11. What is the Board of Trade unit of electrical energy? The electrical installation of a house consists of 30 Tungsten lamps each of 50 C.P. and taking 1·5 watts per candle power. If the mains supply 220 volts pressure, what is the current required to light all the lamps? If the Board of Trade unit is 6*d.* find the cost per hour.

12. Define the terms ampère, ohm, volt, watt and state in what relation they stand to the corresponding C.G.S. units.

An arc lamp takes a current of 7 ampères with a P.D. of 55 volts between the carbons. What is its apparent resistance and what power does it consume? L.M. 1918.

CHAPTER IX

POTENTIAL, CAPACITY, CONDENSERS, ELECTROPHORUS, INFLUENCE MACHINES

86. Charge and Potential.

In § 3 a **conductor** is defined as a substance which readily conveys electricity. The electrons in a conductor are therefore free to move in any direction. We have also seen that the mutual repulsion between electrons constitutes an electric pressure or potential comparable to hydrostatic pressure in a gas.

Consider a spherical conductor (Fig. 128) charged with a surplus of electrons (– ve) and placed in the centre of a large room. This

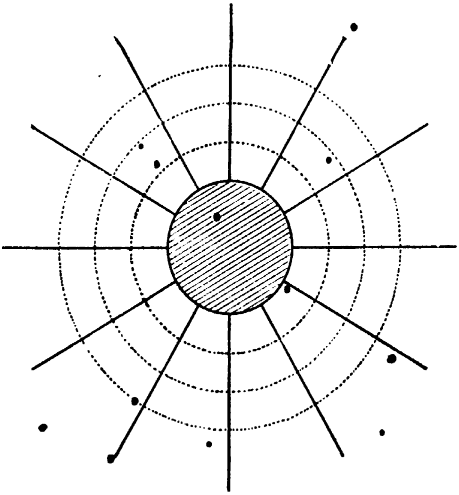

Fig. 128.

– ve charge induces an equal and opposite charge on the sides and walls which are earth connected; lines of force are stretching between each electron and its positive counterpart on the walls. Now lines of force may be likened to elastic strings; there is a force or tension along these strings due to the mutual attraction between the electrons and the induced + ve charges on the walls. There is also a mutual repulsion between each electron and those on the remaining parts of the conductor. Hence the electrons have a tendency to leave the conductor, being urged by forces which constitute a pressure called *potential.* Potential may therefore be defined as the measure of the condition of a body by virtue of which electricity tends to flow from the body to the earth (zero potential).

Positive Potential: the potential of a conductor is said to be + ve when the positive direction of the current is from the body to the earth (*i.e.* the electron-flow is from the earth to the body).

Negative Potential: the potential of a conductor is – ve when the electron-flow is from the conductor to the earth.

An electroscope measures potential.

It is important for the student, at this stage, to realize that the rise of the leaf of an electroscope is a measure of its potential rather than its charge. For in Exp. (ii), § 7, when the ebonite rod is brought **near** the electroscope the **leaf rises** although the electroscope is **on the whole uncharged,** whilst when the electroscope is "earthed," *i.e.* brought to zero potential, the leaf falls, although there is still a large + ve charge on the knob *K*. The rise of the leaf of the electroscope is due to the tendency of the electrons to go to earth—lines of force stretching between the negatively charged leaf and the earthed portion of the jacket of the electroscope.

An electroscope can only be considered to measure charge when it is remote from other charged bodies.

87. The potential of a charged conductor is the same at all points on its surface.

This follows from the definition of a conductor, for the electrons being free to move must eventually come to rest in positions where their mutual repulsions or pressures balance.

Exp. (i). Charge the pear-shaped insulated conductor[1] in Fig. 129 negatively removing all other neighbouring charged bodies. Attach one end of an insulated copper wire to the knob of an electroscope, and move the other end along the surface of the conductor. The rise of the leaf is everywhere the same.

Exp. (ii). Repeat Exp. (i), clamping a charged rod in a burette stand and placing it near the conductor.

Exp. (iii). Repeat Exp. (ii), using a hollow conductor, and show that the potential of its inner surface is the same as that of its outer surface.

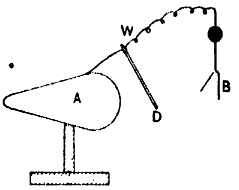

Fig. 129.
A = Pear-shaped insulated conductor. B = Electroscope. W = Wire moved by an Ebonite Rod D.

88. Connection between Charge and Potential: Capacity.

Exp. Support a hollow metallic can on a slab of paraffin wax, its outside surface being connected to an electroscope by copper wire. Lower a charged ball into the can by a silk thread and allow it to touch the inside of the can. Observe the rise of the leaf. (Remember rise ∝ potential.) Double the charge on the can by repeating the process and again observe the deflection. Continue the experiment with a steadily increasing charge on the can.

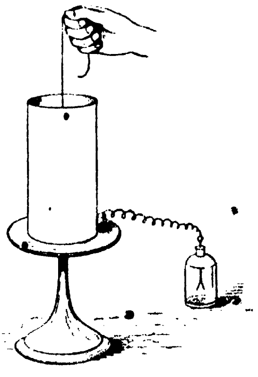

Fig. 130.

Relationship between potential and charge.

It is found that the **potential is proportional to the charge,** *i.e.*

potential (V) ∝ charge (Q),

i.e.
$$V = \frac{Q}{C},$$

---

[1] **In all experiments in Electrostatics, it is essential that all the apparatus should be kept absolutely *dry*, and as *warm* as possible without injuring the apparatus.**

where C is a constant depending on the shape, size and position of the conductor.

$$\therefore \quad (a)\ CV = Q, \quad (b)\ C = \frac{Q}{V} = \text{capacity}.$$

This constant (C) is called the **capacity** of the conductor and equals the ratio of the charge on a conductor to its potential.

It can now be understood why an electroscope may sometimes be used to measure the charge given to it. *For if there are no other charged bodies* near, this charge distributes itself over the conducting surface of the electroscope, and since potential is proportional to charge, the latter may be measured by the rise of the leaf.

89. Surface Density.

Although the potential of a conductor is uniform at all points, it by no means follows that the electrons distribute themselves in a layer of uniform density along its surface. In fact this is seldom the case: for in an irregularly shaped conductor the electrons tend to crowd into the more pointed portions of its surface.

The **surface density** or the amount of charge per unit area of a conductor may be investigated by means of the **proof plane.** (Fig. 131.)

Fig. 131.

Exp. By means of sealing wax attach a small circular piece of copper foil, about the size of a sixpence, to the end of an ebonite rod. Charge the pear-shaped conductor in § 87, and, holding the proof plane by its insulating handle, place the copper disc in contact with a portion of the surface of the conductor. Now the charge on a conductor resides on its outer surface [§ 9 (d)], therefore the charge on the surface in contact with the disc is acquired by the latter; if now the knob of a distant electroscope be touched by the disc of the proof plane, the charge on the disc may be measured by the rise of the leaf.

It is found that the rise is greater when the proof plane has been in contact with the pointed portions of the conductor than when it has been in contact with the more rounded portions.

This result is in accordance with the electron theory; for an electron in the more pointed portions is in equilibrium under the various repulsive forces exercised on it by the electrons in the remaining parts of the conductor. This condition could only exist, if the pressure due to the electrons spread over the greater area of the rounded portions were balanced by a pressure due to a greater charge concentrated on the smaller areas of the more pointed portions.

Action of Points.

We have seen above that the surface density of the charge on a conductor is a maximum on the most pointed portions of its surface. Where the surface actually comes to a sharp point, this concentration may be so great that the particles of air in the immediate vicinity acquire some of the charge and are repelled away from the point along lines of force stretching between the conductor and the surrounding bodies. This is known as a "brush discharge" or "electric wind." The glow of the discharge may be observed in the dark around the pointed portions of any electrical machine in action[1]. It is therefore necessary to avoid all sharp points in the construction of electrical instruments, condensers or aerials, which are designed to retain charges of electricity; on the other hand, use is made of the action of points where a quick discharge of electricity is required.

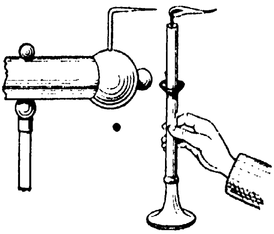

Fig. 131*a*.

Exp. Fix a needle, bent once at right angles, to one terminal of an electrical machine (Fig. 131*a*). Hold a lighted candle near the needle point and work the machine; the rush of charged air particles, constituting the brush discharge, is sufficiently strong to blow the flame away.

90. Experiments on Capacity.

Exp. 1. From an ebonite rod *B* fixed between two insulated stands is suspended a rectangular sheet of tin-foil weighted at one end with a piece of glass tubing. Two silk fibres attached to this glass rod are threaded, as in a Venetian blind (Fig. 132), through holes in the foil and joined together at *D*. The foil is connected at *A* to an electroscope by means of a wire thread.

---

[1] Visible during thunderstorms from lightning-conductors and mast-heads (St Elmo's Fire).

Charge the foil by drawing an electrified ebonite rod over its surface an note the rise of the leaf. Decrease the area of the foil by drawing up the sil thread at *D* and observe that the leaf of the electroscope **rises.**

[Note: the charge on the foil being the same, the potential has risen therefore the **capacity has decreased.**]

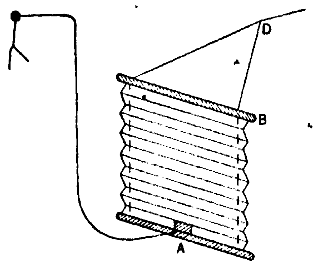

Fig. 132.

Exp. 11. A soap bubble is blown on the end of a glass tube bent once at right angles and passing into a water trap (Fig. 133), the other tube of the

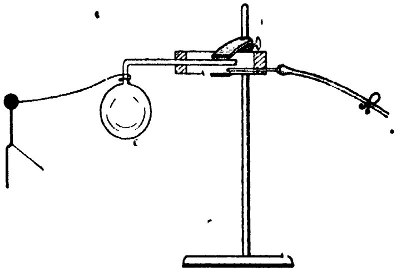

Fig. 133.

trap being connected to a piece of rubber tubing provided with a Mohr clip, the apparatus being fitted to an insulating stand.

A piece of copper wire is wound round the tube at *A* and is connected to an electroscope. Charge the bubble by touching the wire with an electrified rod. Lower the pressure of the gas inside the bubble by opening the clip; the *reduction in the size* of the bubble is accompanied by a *rise* in the leaf of the electroscope (*i.e. capacity* of bubble is decreased).

Exp. iii. Suspend, opposite to the rectangular sheet of foil *A* in Exp. i, a similar piece *B* which is connected to earth by a wire *E* (Fig. 134).

Notice that the leaf of the electroscope **falls** when

(*a*) *B* is brought nearer to *A* (*i.e.* capacity has **increased**),

(*b*) a slab of paraffin wax *P* (or glass or ebonite) is inserted between the two surfaces;

and **rises** (*i.e.* capacity has **decreased**) when

(*c*) the area of the surfaces overlapping is decreased,

(*d*) the distance between the surfaces is increased.

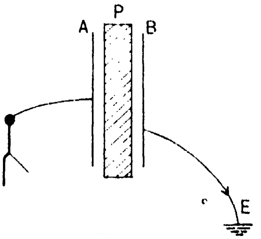

Fig. 134.

This proves that the **capacity** of the system is **increased** by the *presence of the "earthed" sheet of foil* and by the *insertion of the slab of insulating material.*

Exp. iv. Compare the total charge which can be given, before leaking occurs, to the sheet *A*,

(*a*) in the presence of *B*, (*b*) in the absence of *B*, (*c*) in the presence of *P* and *B*.

91. Condensers.

An arrangement of two parallel metallic plates, one of which is charged and insulated, the other "earthed," constitutes a **condenser.** Our experiments have proved to us that the capacity of a conducting plate is greatly increased by the presence of the earthed plate (Fig. 134). For when *B* is near *A*, a charge of opposite sign is induced on the earthed plate. Lines of force stretch across the space between the plates, "binding' or "condensing" some of the charges on *A* to their counterparts on *B*. The potential of *A*, the tendency of its charge to flow to earth, is thus considerably lessened, *i.e.* its capacity is increased. The effect is more marked when certain insulating substances, such as glas paraffin wax or ebonite, are made the media between the plates this medium is called the **dielectric.**

The Capacity of a condenser

$$\propto \frac{\mathbf{K} \times \text{area of the plates}}{\text{distance between the plates}},$$

$$i.e.\ \mathbf{C} \propto \frac{\mathbf{KA}}{\mathbf{d}},$$

where **K** is a constant (called the Specific Inductive Capacity depending on the inductive properties of the medium betwee the plates.

The **Specific Inductive Capacity** of a dielectric is th ratio of the capacity of a condenser when its plates are separate by the given dielectric, to its capacity when *air* only is between.

Table of Specific Inductive Capacities.

Air = 1

Glass	8·45—9·9	Mica	6·33—8·0
Ebonite	3·15—3·48	Paraffin	2·29

From this table it is evident that the capacity of a condenser is greatly increased by the presence of a suitable dielectric, *e.g.* glass or mica.

Types of Condenser.

The Leyden Jar. A glass bottle (Fig. 135) is coated both inside and outside with tin-foil to within a few inches of its upper edge. The remaining portion of its surface is painted with shellac varnish. A metal rod furnished with a knob passes through an insulating cork and makes contact with the inner coating on the bottom of the jar by means of a chain. The two coatings of tin-foil, the outer of which is usually connected to earth by means of a strip of foil, correspond to the two plates of the condenser already described (Fig. 133) with glass between as the dielectric. The condenser is charged by connecting the knob to an electrical machine, *e.g.* induction coil or Wimshurst machine [§ 93].

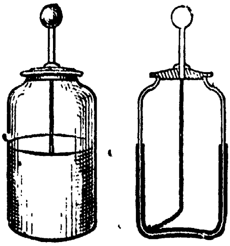

Fig. 135.

Exp. From the secondary terminals of an induction coil lead two pieces of fuse wire each to one of the knobs of two Leyden Jars—the knobs being bent close to one another forming a new spark gap. On working the coil the sparks are now less frequent but much "fatter" and more brilliant.

A battery of Leyden Jars in Parallel.

Leyden Jars may be connected "in parallel" by joining their knobs by a conducting wire, their outer coatings resting on a thick strip of tin-foil. We have thus virtually increased the area of the plates: if C is the total capacity of the system, n the number of jars, c the capacity of each jar, then

$$C = nc.$$

The Condenser of an Induction Coil (Fig. 136) consists of a large number of sheets of tin-foil separated by alternate sheets of waxed paper. At one corner the waxed sheets are cut away together with the odd numbered sheets of tin-foil, leaving the corners of the even numbered sheets of foil to be joined together to form one plate of the combined condenser. At the

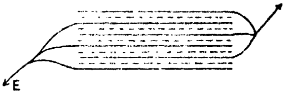

Fig. 136. Section of induction coil condenser. - - - waxed paper. — foil.

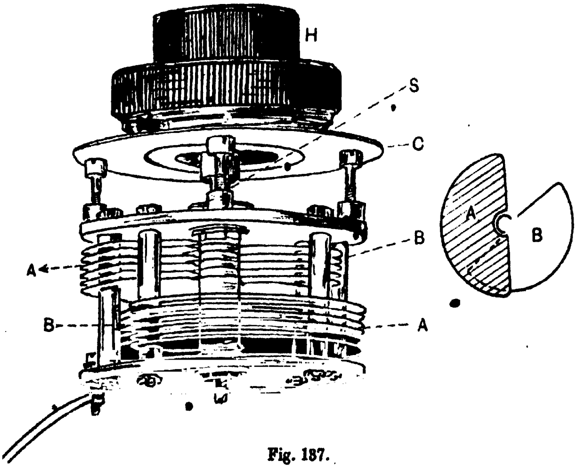

Fig. 137.

opposite corner the even numbered sheets of foil are cut away and the odd numbered sheets fastened together to form the other plate of the condenser. [See § 58.]

Variable Condensers.

Variable condensers for use in Wireless Telegraphy and Telephony are easily constructed from materials supplied by an electrician. Several semicircular aluminium plates *A* (Fig. 137) are supported by suitable rods, and are set parallel to and above one another, at a sufficient distance apart to allow a second set of plates *B* fixed on a conducting spindle *S* to rotate between them without touching. The plates of each set are electrically connected but the sets themselves are insulated from one another. Together they form a condenser, the capacity of which can be varied by rotating the spindle by its insulating handle *H*, thereby altering the effective area of the plates.

A scale *C* marks the capacity of the condenser, corresponding to the various positions of *H*.

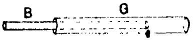

Fig. 138. *B*, brass tube. *G*, glass tube coated with tin-foil.

A very simple variable condenser (Fig. 138) may be made from a glass tube or an old ebonite bicycle pump, coated on the outside with tin-foil: a metal tube slides within and forms the inner coating of the variable condenser.

92. Electrical Machines.

The Electrophorus. Into the lid of a round mustard tin pour some molten shellac or resin and leave it to harden. Obtain a metal disc (Fig. 139) of approximately equal diameter and at its centre attach an insulating handle. Charge the resin slab *negatively* by flicking it with fur and place the disc on

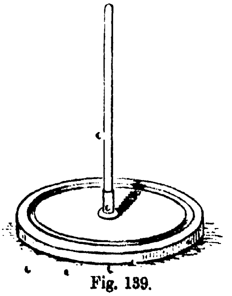

Fig. 139.

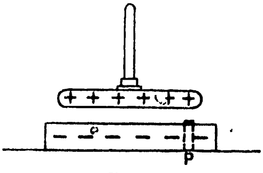

Fig. 140.

the slab. This disc may now be considered to be separated from the slab by a thin layer of air, as it touches at a few points only the *insulating* substance in the dish. Earth the negative charge which is repelled to the upper surface of the disc. Lift the disc by its insulating handle (Fig. 140). Test the sign of its charge (+ve) by bringing it near a charged electroscope.

The charge on the disc may be given to another body by conduction and the operation repeated almost indefinitely. The process of earthing can be eliminated by driving a small metal peg *P* (Fig. 140) through the resin to make contact both with the disc and the earthed jacket when the former is placed on the slab of the electrophorus.

It will be noticed that the charge on the slab remains practically the same: the source of the electricity induced on the disc must therefore be due to the work done by the operator in lifting the disc from the slab, *i.e.* in overcoming the mutual attraction between the induced and inducing charges. [§ 6.]

93. Principle of Electrical Influence Machines.

The principle of the more important electrical influence machines may be readily understood by referring to Fig. 141. *A* and *B* are two conducting spheres which are (*a*) placed in position touching opposite ends of an insulated conducting wire x; (*b*) carried along paths[1] indicated by dotted lines in the figure so as to pass through holes in two hollow conducting spheres *M* and *N*, which, fixed in position and insulated, have flexible wires (S_1, S_2) projecting inside the spheres. Let *N* have a small −ve charge. When *A* and *B* are connected by x, electrons are repelled into *A* leaving *B* positively charged by induction. Suppose *A* and *B* be now taken along their respective paths, then as they pass through the holes in *M* and *N*, touching the small springs S_1 and S_2, they leave behind them [§ 9] their respective induced charges, thereby, as the process is repeated, increasing indefinitely the charges already on the hollow spheres.

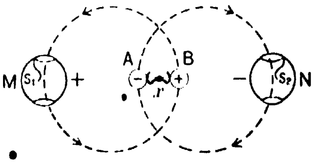

Fig. 141.

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[1] The paths do not lie in the same plane.

The Replenisher.

This instrument was designed by Lord Kelvin in 1867 for use in maintaining at a fixed potential the charge on certain electrical instruments.

A and *B* (Fig. 142) are two cylindrically shaped pieces of metal, insulated from one another and each fitted with a spring (*a*, *b*). An ebonite rod, which can be rotated about a vertical axis, carries with it two curved pieces of metal C_1C_2 fastened on the ends of an ebonite arm projecting at right angles from the rod. Two springs c_1d_1, connected by a wire, make contact with C_1 and C_2 during a portion of their revolution.

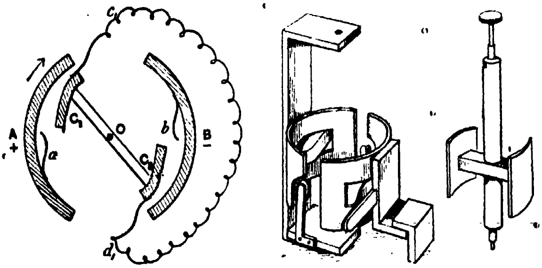

Fig. 142.

Charge the plate *A* +vely by induction. In the revolution of the arm the pieces of metal C_1, C_2 touch the springs c_1, d_1; a negative charge is thus induced on C_1 leaving C_2 positively charged. During the subsequent motion of the spindle these charges remain on C_1, C_2 until the latter simultaneously touch the springs *a* and *b* when the charges are imparted to *A* and *B*. The charges on *A* and *B* therefore gradually accumulate while the spindle is being rotated.

The Wimshurst Machine.

Two circular plates of glass, coated with shellac varnish, are mounted on axles so that they revolve parallel and close to one another, but are geared to rotate in opposite directions when the handle is turned (Fig. 143).

Professor S. P. Thompson has explained the action of this machine by supposing the discs to be replaced by two co-axial cylinders revolving one within the other in opposite directions. In Fig. 144 is depicted a vertical section, the dark lines representing the metallic sectors.

Thin strips of metal are fitted radially on the outer surfaces of these plates and in their rotation are lightly touched by fine metallic brushes fitted into the ends of the conductors *R'S'*, *P'Q'* (Fig. 144) which are fixed diagonally at right angles on opposite sides of the plates. Two metallic collecting combs *A* and *B* embrace the plates, without touching them, at the ends of a horizontal diameter and are separately connected to the brass discharging knobs of the machine.

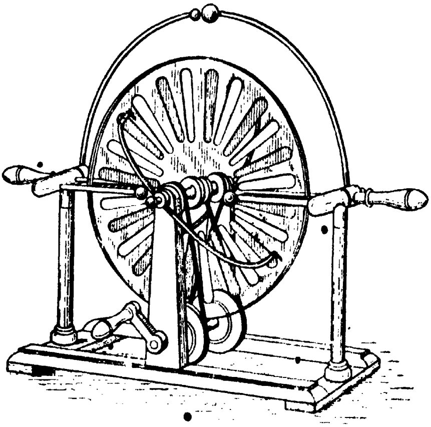

Fig. 143.

Suppose a small negative charge be acquired by one of the sectors[1] on the under side of the inner cylinder. In its rotation it comes under the sector *R'* repelling electrons to the sector *S'* leaving *R'* positively charged. Each outer sector in turn moves on from *S'* in the direction indicated by the lowest arrow, and presently comes under the comb *B* where it is discharged by a positive wind from the meshes of the comb, electrons in excess being left on the comb and on the knob connected with it. In the meantime the strip *R'* has come under the comb *A* from which electrons proceed in a brush discharge, leaving the comb *A* and the attached knob + vely charged. This process is continued indefinitely as the plates rotate.

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[1] When starting the machine, it is often necessary to hold an ebonite rod rubbed with flannel near the rotating discs as "excitant."

The student is advised to study the effects of the charges on *R'* and *S* as they come opposite to *P'* and *S'* and follow the action of the machine through at least two complete revolutions.

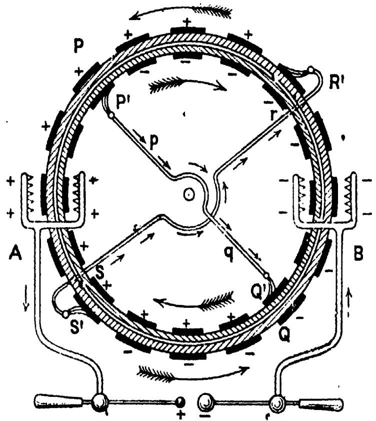

Fig. 144.

94. Lightning and Lightning Conductors.

It is difficult to explain the origin of the enormous differences of potential which occur in Nature during thunder-storms between neighbouring clouds or between a charged cloud and the earth. The latter case may be regarded as that of a condenser on a large scale with the cloud as one plate, the earth as the other, and the air as the dielectric between. When the potential difference between them is sufficiently high the insulation of the air breaks down and a discharge of electricity follows in the form of a flash of lightning the duration of which is of the order of $\frac{1}{1,000,000}$ sec. The flash may be more than one mile in length. This enormous current heats the air in its path causing a sudden expansion with subsequent contraction on cooling which produces a partial vacuum into which the surrounding air rushes with tremendous force. These sudden expansions and contractions of the air result in the noise of the thunderclap.

The electrification of clouds was investigated by Benjamin Franklin (1749) in his famous kite experiments, by which he proved that the properties of atmospheric electricity and those of the electric current were identical.

To protect a building from destruction by lightning, a broad band of iron is fixed to the outside of, but insulated from, the building. One end of the band is fixed to a metal plate buried in wet earth; the other is carried to the highest portions of the building where it terminates in rods furnished with sharp points. The path of the *lightning conductor* from these points to the earth should be as direct as possible.

The *action of points* is well illustrated by the lightning conductor; for the presence of a neighbouring charged cloud causes a stream of oppositely charged particles to flow from the points, thus gradually discharging the electrification on the cloud. If, however, the potential difference is so great that a spark discharge takes place, the conductor offers a straight path of low resistance along which the charges can flow or oscillate without damaging the building and its surroundings.

QUESTIONS ON CHAPTER IX

1. Given glass tubing, some copper wire, silk thread, pith balls, etc., devise a form of apparatus for investigating the arrangement of the lines of force in an electric field. Draw diagrams showing the results that would be obtained using (*a*) equal like charges, (*b*) equal unlike charges.

2. Describe experiments to show clearly the distinction between potential and charge. How would you compare the densities of the charge on two small areas of surface? How can there be a difference of density where there is no difference of potential? O.L.S. 1920.

3. What is meant by "the surface density at a point"? You are given an insulated charged hollow pear-shaped conductor in which a hole has been drilled at the top. How would you proceed to investigate (i) the surface density of the charge on (*a*) the outside, (*b*) the inside surfaces of the conductor, (ii) the potential of (*a*) the outside, (*b*) the inside surfaces? What results would you expect? Give your reasons.

4. You are given a charged insulated conductor *A* and an uncharged hollow conductor *B*. How would you proceed to obtain on *B* a charge of like sign twice that on *A*? Would your method give accurate or only approximate results?

5. A body is charged to a potential of V units and possesses a charge of Q units. Explain fully what is meant by these statements.

In what circumstances may (*a*) a body possess a charge and be at zero potential, (*b*) be uncharged and yet have a potential differing from zero? L.M. 1918.

6. A and B are two parallel conducting plates each separately connected to an electroscope. If A is charged and insulated whilst B is earth connected, draw diagrams of the lines of force between A and B, when (*a*) they are some distance apart, (*b*) they are near to one another. Give the indication of the electroscopes in each case. What effects follow the insertion of a slab of paraffin wax between the plates?

7. Define "capacity." Describe some simple experiments to illustrate the action of a condenser. Explain how the leaf of an electroscope may be caused to diverge using a Daniell's cell as the charging agent [§ 14]. L.M. 1918.

8. Draw a sketch of a Leyden Jar, and state why its capacity is increased when its outer coating is effectively connected to earth.

9. A roll of tin-foil is held in an insulating stand. It is then unrolled and placed on a thin slab of paraffin wax lying on the ground. Account for the large differences in the amount of electricity which can be given to the foil in the two positions.

10. A strongly electrified glass rod is fixed in an insulating stand. An experimenter holds his hand near the rod and drops pennies into a hollow can which rests on an ebonite block vertically below the rod. Account for the charge acquired by the can.

11. What is meant by the "action of points" and in this connection explain the working of a "lightning conductor"? Devise laboratory experiments to illustrate on a small scale the action of a lightning conductor.

12. What is an electrophorus? Describe its action, illustrating your answer by diagrams showing the electrification of the separate parts during the various stages of the experiment.

13. Describe and carefully explain the construction and mode of working of some electrical machine.

CHAPTER X

THE GENERATION AND PRACTICAL APPLICATIONS OF ELECTRICITY

95. The Dynamo. The dynamo gives us a means of transforming the mechanical energy of a steam engine, turbine, or water wheel into the energy of the electric current. Cables convey the current through small or great distances as may be required, but at any point in the external circuit the current may be used for heating and lighting or directed through suitable machines for power development.

Earth Inductor and Simple Dynamo (Figs. 145 *a* and *b*).

Demonstration. *AB* is a rectangular coil $3\frac{1}{2}'' \times 2\frac{1}{2}''$ made of 25 turns No. 26 copper wire. A knitting needle is used as the axis of the coil and passes through two brass supports S_1S_2 terminating in a small handle *H*. The coil rotates between two soft iron pillars P_1P_2, the bases of which rest on a double pole

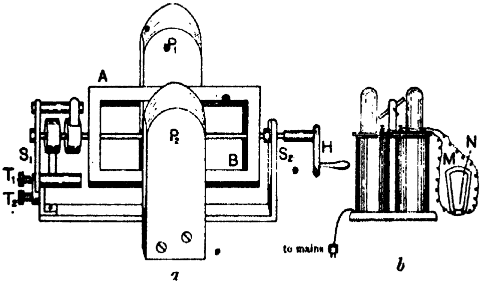

Fig. 145.

electromagnet operated from the lighting mains. The ends of the wires from the coil are securely fastened to two brass slip rings (Fig. 146 *a*) which are insulated from the knitting needle by ebonite cores. Light brass or copper strips rest on these slip rings and connect to two terminals $T_1 T_2$, from which leads run to a micro-ammeter *M*.

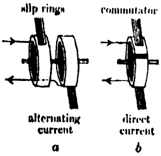

Fig. 146.

Slowly but steadily rotate the coil by means of the handle from the vertical position through the horizontal until it has passed through an angle of 180°. The needle of the micro-ammeter moves in one direction at first slowly, then more rapidly as the plane of the coil passes through the horizontal position and afterwards the needle gradually comes back to zero. On continuing the rotation of the coil through the second half of the complete cycle the needle moves in a similar manner but in the opposite direction.

(1) Having turned on the current through the electro-magnet, (2) repeat this experiment—turning the handle more rapidly. Explain the effects produced.

We have seen in § 41 (*b*) that when a wire or conductor is moved so that it cuts lines of force in a magnetic field, an electric current is induced in it, the direction of the current being determined by the extension of Ampère's rule.

Let Fig. 147 (*a*) represent the rotation of a wire or conductor through the magnetic field produced by two magnetic poles N, S. Starting from position 1,

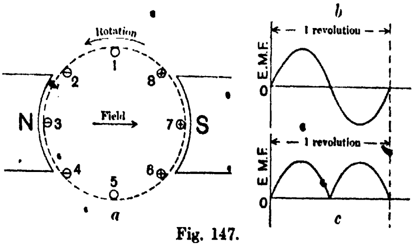

Fig. 147.

it is easily seen that the wire is moving **along** lines of force, not cutting them, and therefore no E.M.F. is produced. As it rotates, the strength of the field increases, and with it the resultant E.M.F. which is proportional to the rate of cutting lines of force [§ 58], until in position 3 this E.M.F. is a maximum. As the wire moves into position 5, the E.M.F. gradually weakens to zero. Under the S-pole the process is repeated the current direction being, of course, reversed.

Fig. 147 (*b*) shows the changes in the induced E.M.F. corresponding to one complete revolution.

The rotation of the coil through 360° in this exp. gives us a complete electrical cycle and, as will be seen on reference to Fig. 147 (*b*), an alternating current is produced by the revolution of the coil in the field formed by the two magnetic poles. This current changes twice in each complete revolution from zero in the vertical position to a maximum in the horizontal.

A coil rotated in the *Earth's field* alone is called an **Earth Inductor,** but a coil rotated in a field increased by means of an electro-magnet is a **dynamo** in its simplest form. In a dynamo, the rotating coil is called the *armature* which in its rotation cuts the magnetic field produced by the *Field Magnets*.

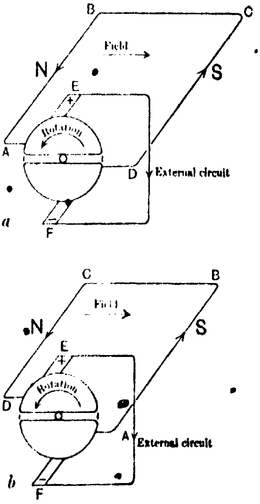

Fig. 148.

The Simple Commutator.

When a direct current is required in the external circuit, a split ring commutator (Fig. 146 *b*) is substituted for the two slip rings. The action of the commutator is readily understood on reference to Fig. 148 (*a*), for, if *ABCD* represents the coil, then when *AB* comes under the N-pole the current generated in the coil by the rotation flows from *B* to *A* and out of the machine through the brush *E* (+), whilst if *CD* is under the N-pole (Fig. 148 *b*) the current now flows from *C* to *D* and out through the brush *E* which therefore is still the positive brush. When a commutator is used, the rise and fall of the induced E.M.F. is as represented in Fig. 147 (*c*).

On consideration of the curves showing the E.M.F. produced by a simple dynamo, it is evident that owing to the corresponding fluctuation of the current, a dynamo of this description is of little use for either lighting or heating. If however a number of wires or conductors are fitted round the armature at regular intervals, and connected in series, the current is not only greatly increased, but is much more uniform, for when the E.M.F. of one coil or conductor is least, the E.M.F. of another will be approaching a maximum.

96. The Drum Armature.

The Drum Armature, in direct current machines, is constructed on this principle and has now completely superseded all other types.

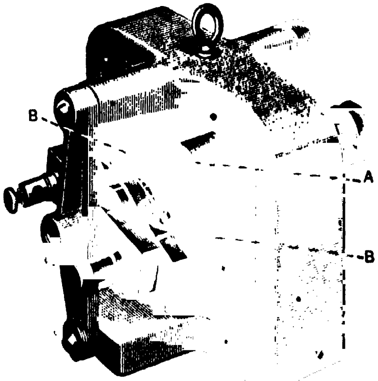

Fig. 149. Small portable dynamo showing drum armature with slots. *A*, Drum armature. *B*, Field Magnets.

In this armature, grooves (Figs. 149, 150) are made parallel to the axis of rotation at regular intervals along the curved surface of a laminated cylindrical iron core which rotates between the field magnets. The conductors, which are usually thick strips of copper, are laid in these grooves, and are suitably insulated from the core. The strips thus form sets of coils which are connected in series, by methods varying with the particular design, to the commutator which is situated on

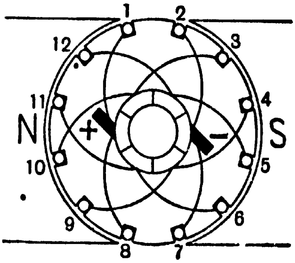

Fig. 150.

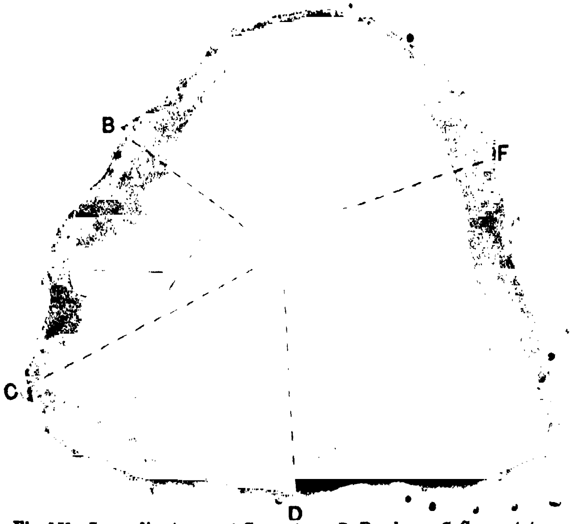

Fig. 151. Large direct current Generator. *B*, Brushes. *C*, Commutator. *D*, Drum armature showing windings. *F*, Field Magnets.

one side of the drum. Fig. 147 may now be used to represent an armature with 8 slots, whilst Fig. 150 represents an end view of a drum armature with 12 slots which requires a commutator with six sections.

Imagine the drum (Fig. 150) to be rotated in a counter-clockwise direction, and apply the rule in § 41 (*b*) or 54; a direct current will be collected by the brushes, the current entering the external circuit from the brush marked +.

The segmented commutator.

In modern industrial practice the number of conductors wound on an armature is very great, necessitating a commutator of many sections (Fig. 151). The making of a commutator requires careful design and clever workmanship in order that it may work efficiently at very high speed, *e.g.* 600 revolutions per minute. It is built up of copper segments, with mica insulation, held together by clamp rings, which again are insulated from the copper by mica cones. Brushes of high grade graphite carbon are mainly used. In a good commutator sparking between brush and commutator should be hardly perceptible.

97. The Field Magnets and Winding of Dynamos.

In many dynamos the current required by the field magnets is obtained from the dynamo itself by "tapping" or "shunting" current from the external circuit. On starting the machine there is generally sufficient residual magnetism in the field magnets to generate a small initial current, which, in its turn, on passing through the magnet circuit increases the field, and thus creates a steadily rising E.M.F. until the maximum output is obtained.

Two **methods of winding** the field coils require special attention.

Series Winding. In this method (Fig. 152 *a*) the field magnets are excited by wrapping round them a few turns of stout copper wire in **series** with the external circuit, so that all the "load[1]" current passes round the field magnets. The introduction of resistance into the external circuit (*e.g.* lamps, motors, etc.) will therefore be accompanied by a reduction in the current in the field coils and a consequent lowering of the generated E.M.F. It will be seen therefore that a small variation in the resistance of the external circuit will cause big changes in the current produced by the dynamo.

---

[1] **Load** is the term given to the work done by the current in the external circuit. The quantity of this current at a constant pressure is a measure of the power required to operate the **load**, viz. the various motors, lamps, etc. of the circuit.

Shunt Winding. Here the field magnets are excited by coils consisting of a large number of turns of thin wire **in parallel** with the external circuit. (Fig. 152 *b.*) When the resistance in the external circuit is increased, this will cause a larger fraction of the main current to flow in the field coils [see § 70] thereby producing a stronger E.M.F. The current in a circuit maintained by a shunt wound dynamo is therefore likely to be more constant than that maintained by a dynamo which is "series wound."

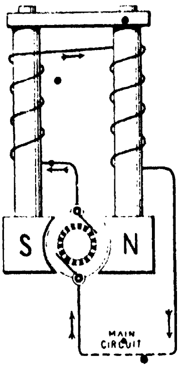

Fig. 152 *a*. Series winding.

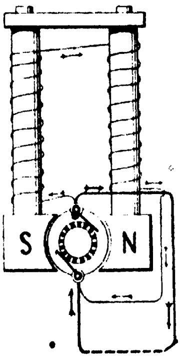

Fig. 152 *b*. Shunt winding.

Compound Winding.

To obtain a machine which will maintain a constant voltage with varying loads, it is found necessary to use a small series field in conjunction with the shunt field. This arrangement is known as *Compound Winding.*

98. Economical Distribution of Power.

It was found in § 80 that in a dynamo

POWER DEVELOPED = CURRENT × E.M.F.,

i.e. WATTS = AMPÈRES × VOLTS.

Now one of the largest items of expense in the transmission of electric power from the generating station to the factories, etc. is the high cost of very thick copper cables: the greater the current (ampères) the thicker the cable that is required. Consequently it

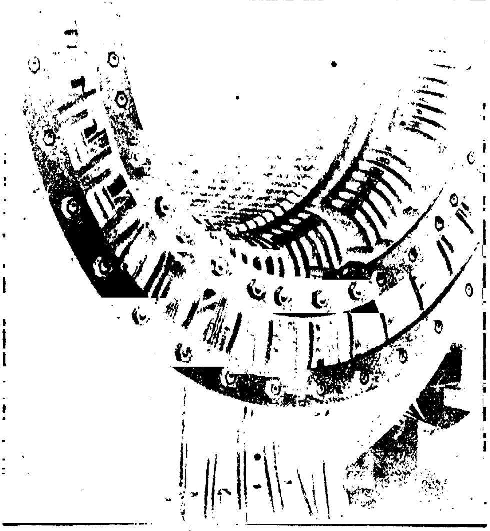

Fig. 153. Turbo-Alternator. The Stator (15,000 K.W. machine).

is found to be far more economical to use high voltages with a comparatively low current since a much thinner cable will carry the smaller current.

E.g. 5000 watts = 5 kilowatts = 1000 volts × 5 ampères
= 100 volts × 50 ampères.

Thus in a modern machine generating 12,000 kilowatts as high an E.M.F.

as 6000 volts is maintained: and even with this voltage the cables have still to carry 2000 ampères.

99. Turbo-Alternators.

The generation of high voltages by a direct current machine, such as has been described, would produce almost impossible conditions. The enormous potential (pressure) differences between the working parts would cause leakage and sparking across the brush contacts and between the commutator segments. In most high power machines it is now customary to reverse the conditions of coil and magnet by keeping the *coils stationary* while *rotating* the *field magnets.* This is effected by winding the coils round a hollow cylindrical core (*the stator*) (Fig. 153). A *rotor* (Fig. 154), an electromagnet of

Fig. 154. Turbo-Alternator. Assembling the Rotor.

two or four poles, is then spun or revolved at a high speed by a steam turbine, which also, on the same shaft, works a **low voltage** direct current dynamo in order to provide the exciting current for the rotor. A high voltage *alternating* current, which is collected without the aid of a commutator or slip rings, is therefore produced in the stator, and is sent along cables to distant sub-stations where it is "transformed" into voltages suitable for lighting and power.

100. Electric Motors [see also § 53, Exp. (iii)].

Exp. Place the simple dynamo described in § 95 between the poles of the electro-magnet (the split ring *commutator* Fig. 146 *b* must be substituted for the slip rings in Fig. 145). Connect the terminals T_1, T_2 to the terminals of a four-volt accumulator. When the current is passed through the magnets and the machine, it is found that the armature rotates at a great speed.

We have seen in § 40, that a solenoid through which a current is passing behaves as a magnet possessing N- and S-poles. The armature is in effect a rotating solenoid which tends to set itself in such a position that its N-pole is opposite the S-pole of the field magnet. The momentum of rotation will however carry the armature past this position and bring into action the commutator (Fig. 146 *b*) which reverses at the same moment both the direction of the current and the polarity of the rotating solenoid. Hence this rotary motion is continued in phases of half revolutions by the automatic action of the commutator.

Any suitably designed dynamo can therefore be used as a motor, provided that care be taken to prevent too large a current from passing through the coils when the machine is started. This is usually effected by a device made on the principle of the sliding rheostat [§ 69].

101. The Magneto.

The gases in the cylinder of an internal combustion engine, *e.g.* the petrol motor of an automobile, are exploded by means of an electric spark. It is often inconvenient to carry on the car an accumulator for providing the necessary current and it is therefore found advantageous to utilize the energy of motion of the engine in the generation of this current. In the magneto are embodied (*a*) a *dynamo* for the generation of the current, (*b*) an *induction coil* for the transformation of this current into one of sufficiently high voltage to cross the gap between the two nickel points of the sparking plug which is fitted into the head of the cylinder.

The magneto then consists of a small dynamo, the armature of which is rotated by the engine. Around this armature is wound a secondary coil consisting of a large number of turns of fine wire connected to a condenser. A rotating contact breaker in the primary circuit, actuated by either the engine or an electric motor, produces an intermittent current which induces a current of high E.M.F. in the secondary of sufficient pressure to provide the necessary spark [see § 58] at the gap situated in the sparking plug.

A separate starting mechanism is required to provide the initial spark to set the engine in motion, but when once it is started the generation of electricity is continued by means of the magneto.

102. Electric Lighting.

Filament (Vacuum) Lamps.

Vacuum incandescent electric lamps are too well known to need a detailed description. The old carbon filament lamp (Fig. 155) has long ago fallen out of use owing to its low efficiency[1], and to the steadily increasing opacity of the globe caused by the deposition of carbon on the glass. This type has been superseded by the metal filament lamp in which the carbon filament is replaced, as a rule, by a length of drawn Tungsten wire.

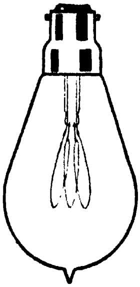

Fig. 155. Carbon filament lamp.

The bright grey powdery metal, Tungsten, is compressed in a steel mould by hydraulic power until the particles adhere to one another. They are then solidly welded together by an electric current, and the resulting "billet," kept at a high temperature, is passed in succession through machines which hammer it vigorously on all sides until it takes the form of a long rod. The metal is now ductile and may be drawn out into wire of ·001 inch in diameter. A length of 20 to 40 inches of this wire is suspended in a bulb (Fig. 156) its ends being connected to the cap contacts by two platinum "leading-in" wires which pass through the cemented cap. The bulb is then pumped vacuous and sealed off at the tip.

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[1] Efficiency = lumens per watt [§ 80].

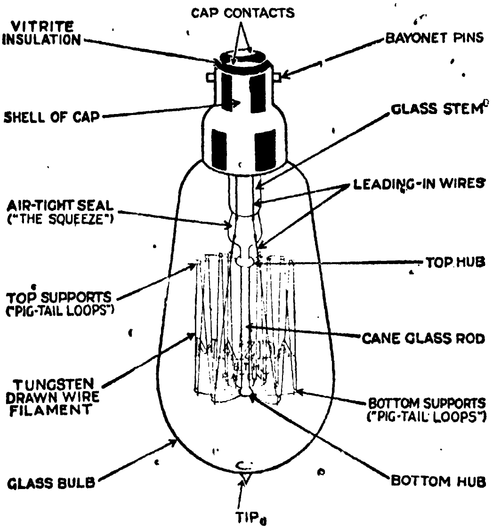

Fig. 156.

103. The Gas-filled lamp.

The efficiency of the metallic filament lamp has been greatly increased in recent years by the introduction into the bulb of the inert gas, Nitrogen. The presence of this gas, at atmospheric pressure, permits that the filament be maintained at a much higher temperature than is possible in a vacuum and also prevents combustion of the filament; consequently a much brighter light is given out.

104. Efficiency[1] of Electric Lamps. The "Lumen."

The **efficiency** of a lamp is the *ratio* of the *light* given out to the *power* expended.

A new standard of illumination, the "lumen," has recently been adopted, which makes it possible to obtain a far better measure of the **total** amount of light emitted by a lamp than by using the old "Candle Power[1]" unit which measured the illuminating power of a lamp **in one direction only.**

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[1] Efficiency = lumens per watt [§ 80].

The **"lumen"** is the **amount** of light falling on an area of one square foot held one foot from a standard candle. The **total amount** of light given out by a lamp is measured in terms of "lumens" and by comparison with the electrical power (watts) consumed, a measure of the efficiency of the lamp can be obtained.

Table of Efficiencies.

Introduced	Type of Filament	Approx. efficiency lumens per watt	Approx. temperature of filament
1880	Carbon	2·25	1800° C.
1906	Graphitized Carbon	3·25	1880° C.
1905	Tantalum	4·5	1950° C.
1906	Tungsten (vacuum)	7·4	2050° C.
1914	,, (gas filled)	12·5	2400° C.

105. Wiring.

The wiring of a building is always carried out with the lamps in "parallel," because by this method (1) a defect or breakage in one lamp will not affect the remainder of the circuit, and (2) with a constant E.M.F. supplied by the generator, the addition to the circuit of more lamps does not affect the quantity of current passing through any particular lamp. Fig. 157 represents a system of wiring which includes the switch.

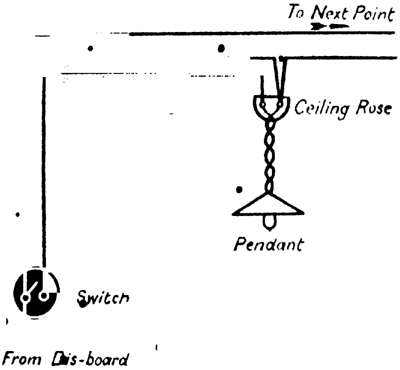

Fig. 157.

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[1] See *Experimental Science*, Physics, Sect. V, Light, § 173.

106. The Electric Arc. (Davy, 1806.)

Fig. 158 illustrates an apparatus for producing an electric arc for use in an optical lantern. The carbons are connected through a suitable resistance to the power mains, the thicker carbon to the positive terminal. When the carbon points are first brought together, by means of a rack and screw adjustment, a large current flows which warms the junction; then, whilst the current is still passing, the carbons are separated to the extent of about a quarter of an inch. The discharge, which is called an **electric arc,** is characterized by intense heat and light, the main sources of light being the ends of the rods.

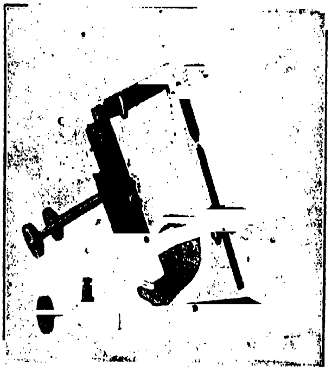

Fig. 158.

Exp. To illustrate the Arc. If the focussing lens of the optical lantern is removed, and the arc drawn back in the body of the lantern, it is possible, by means of the condenser, to project a brilliant and enlarged picture of the arc on a lantern screen. It is observed that the brighter portion is the tip of the positive carbon where presently a glowing crater of hot substance is formed by the impact of electrons projected at great speeds from the negative carbon. Bubbles of hot gas, volatilized carbon, are noticed on the negative pencil. Temperatures of over 3500°C. are developed at the end of the positive pencil and within the arc. The carbons gradually volatilize and burn away, the positive at the greater rate; it is therefore necessary to keep them at the correct distance apart by hand adjustment or by some suitable mechanical device worked by the current itself. In optical lanterns, the positive carbon is made with a core of soft carbon to allow the crater to form easily, the diameter being about twice that of the negative, so that both may burn away at approximately the same rate.

Parallel Carbons.

The efficiency of many of the lamps is lowered by the obstruction which the tip of the negative carbon offers to the light emitted from the glowing positive crater, so that the light is reduced in certain directions. In the "parallel Arc" two long horizontal carbon pencils are fixed near and parallel to one another with their ends pointing in the direction where the light is required. A suitably placed electromagnet, actuated by part of the current, produces a transverse magnetic field between the two carbon tips, and forces the arc outwards [§ 41] thereby preventing it from running up the rods. By this method an arc of high candle power and efficiency is obtained.

107. The Pointolite Lamp. (Ediswan Company.)

The great advantage that the arc lamp possesses as a point-source of light of great intensity, is that it allows the operator, in optical work, to focus rapidly and obtain the sharpest definition. This advantage has been further embodied in the Pointolite incandescent gas filled lamp (Fig. 159), in which an arc is formed between a metal ionizing filament *F* and a Tungsten bead *B* (the positive element). The Tungsten bead becomes white hot and emits a light of intense concentration. As the lamp requires no attention when in use, it is ideal for optical work and for colour matching, gauge testing and other experiments where a small and brilliant source of light is needed.

Fig. 159.

108. Electric Heating.

Electric Kettles, Irons, Toasters, Cookers and Heaters in general are constructed on one principle—viz. the *Joule Effect*, § 81. Coils and wires of high resistance are heated by an electric current in all these contrivances.

The Electric Furnace and Arc-Welding.

In the electric arc very high temperatures are developed because the great energy of the electric current is converted into heat energy in a very small space; the heat is, as it were, concentrated: this fact is utilized in the electric furnace.

In the *Moissan type* of furnace (Fig. 160), the heat obtained from the arc, which is formed between two thick carbon electrodes, is reflected downwards on a crucible containing the substance to be melted; or again the mixture to be fused is placed in a crucible, and a strong current passed between two carbon rods immersed in the mixture. By this latter process Calcium Carbide (CaC_2) and Carborundum (SiC) are made.

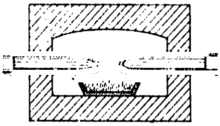

Fig. 160. Electric Furnace.

In the *Electric Vacuum* Furnace of the General Electric Company, U.S.A., the current is passed through a graphite helix surrounding the

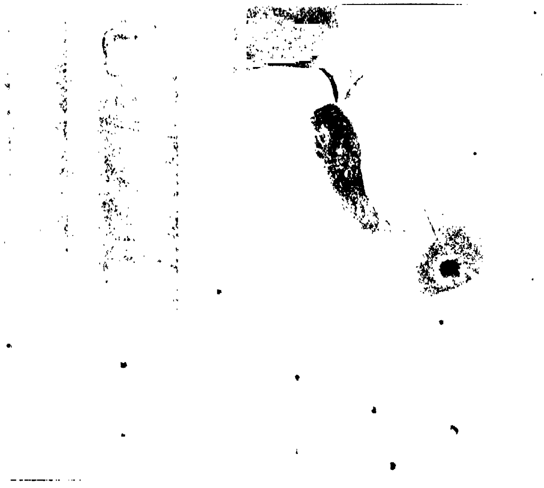

Fig. 161. Welding by means of the Electric Arc.

object to be heated, the whole being enclosed in a steel vacuum chamber; a temperature of 4000°C. has been obtained by this method.

By means of the heat of the electric arc pieces of metal may be entirely melted away, or cut or welded together. In the Metropolitan-Vickers Electric Arc Welding Process (Fig. 161) an arc is formed between a carbon pencil and the metal to be worked. In general the carbon pencil, held by the operator in a specially insulated holder, forms the negative electrode, and the worked metal is connected to the positive pole of the electric supply. A current of 300–400 ampères is passed across the arc. If it is required to deposit one metal on a larger piece of another, small chippings of the former are melted on to the latter by the intense heat of the arc.

109. The Electric Telegraph.

The Morse Writing Instrument. The Morse Code.

In Line Telegraphy, signals are usually transmitted between stations by the Morse Code in which the letters of the alphabet and the numerals are represented by dots and dashes (or short sounds and long sounds) according to the table below.

The Morse Code.

A · —
B — · · ·
C — · — ·
D — · ·
E ·
I · ·
S · · ·
H · · · ·
F · · —
G — — ·
K — · —
P · — — ·
J · — — —
Y — · — —

N — ·
V · · · —

U · · —
T —
M — —
O — — —

L · — · ·
W · — —
R · — ·
X — · · —
Q — — · —
Z — — · ·

Numerals.

1 · — — — —
2 · · — — —
3 · · · — —
4 · · · · —
5 · · · · ·

6 — · · · ·
7 — — · · ·
8 — — — · ·
9 — — — · —
0 — — — — —

Both a **Morse Sender** (Fig. 162 *a*) and a **Morse Receiving Instrument** (Fig. 162 *b*) are usually inserted in the circuit at the various stations. The *Sender* is essentially a two way switch (Fig. 14). In its normal position the local "Receiver" is connected to the line; but when the stud is depressed a current can be sent to a receiver at a distant station. Fig. 162 *c* explains 162 *b*.

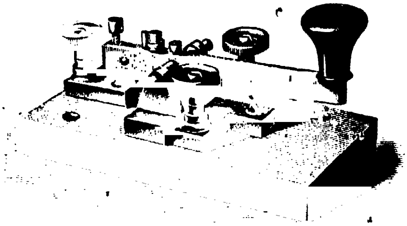

Fig. 162 *a*. A Morse Sender.

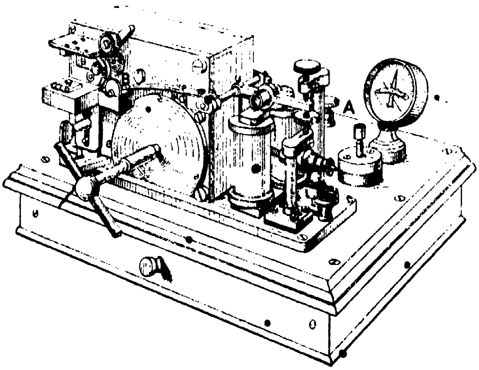

Fig. 162 *b*. A Morse Writer and Sounder.

In the latter a *Morse Sounder* is also shown which is constructed on the principle of a vibrating contact breaker. [§ 58.]

In the receiving instrument Fig. 162 *c*, a paper tape is unrolled at a uniform rate automatically by means of a clock-work mechanism. When the key is pressed at the distant sending station, a current from the line passes through an electromagnet *E* drawing down a soft iron armature *A*, pivoted at *P* thereby causing the inked style *A'* to touch the moving paper tape. The key is depressed for long or short intervals, according to the code, causing the style *A'* to remain in contact with the paper for corresponding periods It is often found more convenient to receive signals by sound using the Morse Sounder.

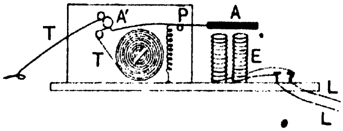

Fig. 162*c*. *LL*, to line. Diagram of Morse Writer.

Exp. To illustrate the Morse Sounder.

Alter the connections of an electric bell (Fig. 163) so that the electromagnet is placed in a circuit by itself containing a battery and suitable key. Remove the bell and screw in a heavy brass terminal at *C*, so that whenever a current passes round the magnet the vibrator is drawn inwards hitting the screw *C* with a sharp tap. Messages can be sent by means of this instrument in the Morse Code, the dashes and dots being represented by long and short intervals between the clicks; the signals being conveyed to the operator by sound he can give his attention to writing down the message.

It is evident that the strength of the current through a circuit of considerable length, extending say from London to Plymouth, would be insufficient to work a Morse sounder or similar instrument. A device known as a **Relay** is therefore used by which a feeble current brings a stronger one into action.

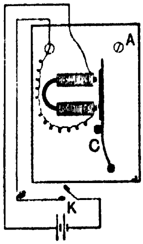

Fig. 163. Electric Bell adapted to illustrate Morse Sounder.

Exp. To illustrate the Post Office Relay.

Connect the brass screw at the end of the vibrator of the electric bell (Fig. 164) to the terminal *A*, which is joined to one pole of a four volt accumulator, *B*, the circuit being completed from the other pole of the accumulator through a model motor, *M*, for instance, to the terminal *C*. On pressing the key *K*, the vibrator being drawn towards the electromagnet makes contact at *C* and thus permits the stronger current from the accumulator to work the motor.

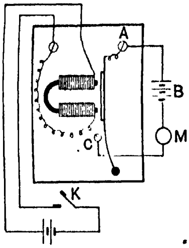

Fig. 164. Electric Bell, adapted to illustrate P.O. Relay. *B*, Accumulator, *C*, Leclanché Battery.

In recent years by the use of a valve amplifier [§129] the relay has been modified for sending messages over very great distances.

110. The Duplex System is a method by which messages may be sent in **two** directions on **one** wire. Fig. 165 explains this system. When the key at the transmitting station *A* is pressed, the battery at this station sends a current along the line wires, which are carefully suspended on telegraph poles or sunk underground as insulated cables, to the receiving station at *B* where it actuates a suitable instrument and returns through the earth by means of plates sunk into the ground. On receiving the message, the operator at *B* can reply; for by pressing his key a current traverses the circuit in the opposite direction and works the instrument at *A*.

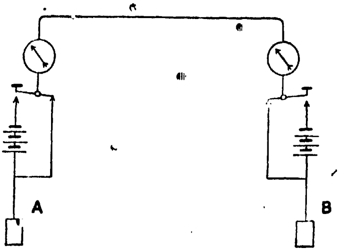

Fig. 165.

The **Duplex System** of sending single messages on *one* wire in *opposite* directions is extended to include the transmission of *two messages* through *the same wire, one from each end, at the same time.* The two methods employed are named (*a*) the **Differential** and (*b*) the **Bridge** method. The principle of the simpler **Differential System** may be explained briefly by the use of Fig. 166, where the simplest form of receiving instrument, a galvanometer (*G*), is shown. The instruments are identical at the two stations and both transmitted and received currents pass through each galvanometer; the transmitted current, however, from the sender's point of view does not affect the sender's galvanometer, but only the instrument at the far end of the line. This is effected by the following device. Each galvanometer is furnished with a *Differential coil* consisting of two parts wound in *opposite* directions, in one of which an adjustable resistance is placed so that the sender's current, producing equal but opposite forces at the centre of the coil, does not affect his galvanometer needle. The received current, however (indicated by dotted arrows in Fig. 166), passes in *one direction* only round the coil and therefore affects the needle.

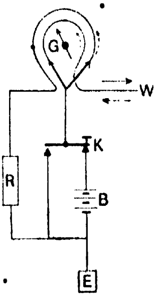

Fig. 166. *B*, Battery, *K*, Key, *R*, Adjustable Resistance. Full arrows show direction of transmitted current, dotted arrows that of received current. *W*, Line wire to similar instrument at other end.

111. The Bordeaux System (G.P.O.).

By the use of a very ingenious instrument it is possible to send five or six messages in the same direction on the one wire. An electrically maintained rotating and commutating device puts an operator into electrical communication with his corresponding instrument at the other end of the wire for a fraction of a second, during which he has time just to transmit one signal. The other sending instruments are similarly connected in turn, so that supposing six operators are using the one wire, each can send a signal from his instrument every sixth interval. These intervals are short and recur rapidly but regularly so that the operator can quickly accustom himself to the rate of working and synchronize his tapping of the transmitting instrument with the period during which the wire is under his sole control and is in touch with the corresponding receiver at the far station.

112. The Microphone and Telephone.

In the telephonic transmission of speech by electricity, use is made of the fact that loose carbon contacts offer great *variations* *of resistance* to the passage of a current. As the particles of carbon forming part of a circuit are compressed or loosened by the vibrations caused by the voice, so the current in the circuit increases and diminishes.

Exp. To show change of resistance with a varying contact.

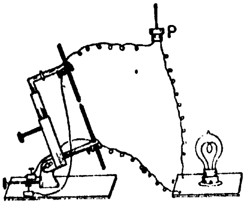

Fig. 167. *P*, Pendant.

If the two poles of an electric lamp pendant, *P*, are connected in series by wires which carry the current (1) through a carbon filament lamp and (2) across the junction of an arc lamp (Fig. 167) only a dull red glow is observed in the former when the carbon pencils of the latter are in slight contact; but if the carbon pencils are brought more tightly together, the resistance is greatly reduced so that the incandescent lamp glows brightly.

113. The Microphone Transmitter.

The vibrations produced in the air by the human voice cause a carbon diaphragm *C* in the transmitter (Fig. 168) to vibrate, thereby causing variations of pressure on carbon granules which fill the space between *C* and *A*. When the telephone is used as transmitter, a current from a local battery of cells is maintained across this space *CA*, and variations in this current cause corresponding variations, through a transformer, at the receiving station. The large variations in the resistance

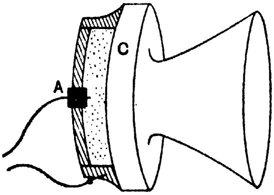

Fig. 168.

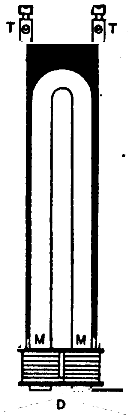

Fig. 169.

which the granules offer cause corresponding fluctuations in the current flowing into the line.

114. The Bell Telephonic Receiver was invented by Graham Bell in 1877 and is called the Telephone. The current from the line passes through *MM* (Fig. 169) and magnetizing the core draws inwards a sheet iron diaphragm *D*. The vibrations in the diaphragm of the microphonic transmitter cause rapid variations in the line current, and this changing current affects the strength of the magnetization in the receiver, throwing the diaphragm *D* into a vibration in sympathy with the vibrations of the diaphragm of the transmitter. The vibrations of the human voice are therefore accurately reproduced in the receiver.

Fig. 170 represents the connections in a simple telephone circuit in which the calling up bell is rung from the one station only (on the left of the diagram). When the receiver on the right is on its hook, connection is made with the bell circuit only and the operator at the other end may be rung up by pressing the button *B*. On taking the receiver from its hook, a spring puts the telephone in circuit and releases the bell contact; conversation may then proceed.

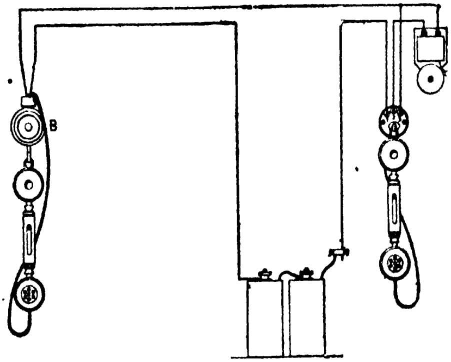

Fig. 170.

Exp. To illustrate the microphone and telephone.

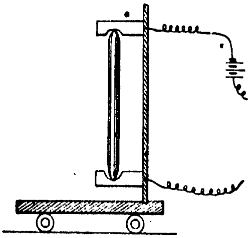

Fig. 171.

A battery and a telephone are placed in series with a microphone, which in a simple form consists of a long carbon pencil resting loosely between two conducting supports (Fig. 171). Place a watch on the stand: the vibration of its mechanism causes great variations in the resistance of the carbon contacts, and produces corresponding changes in the amount of current passing round the circuit; consequently equally varying currents through the telephone. Thus the sound made by the working parts of the watch is greatly magnified in the telephone.

Exp. To show that the Bell-receiver may also be used as transmitter.

The Bell telephone receiver was first invented for use as a transmitter; the principle of its working may be illustrated as follows:

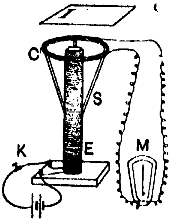

Fig. 172. *K*, key, *S*, insulated stand.

E is a strong electromagnet (Fig. 172) fixed in a vertical position. *C* is a horizontally placed coil consisting of a large number of turns of copper wire whose ends are connected to a micro-ammeter *M*. If, when a steady current is passed through the coil, a large sheet of iron *I* is moved quickly up and down above the pole of the electro-magnet, currents are induced in the coil *C* by the motion of the iron in the magnetic field and are recorded by the micro-ammeter *M*.

In the Bell telephonic transmitter the vibrations of the sheet iron diaphragm *D* (Fig. 169) caused rapid variations in the magnetic flux passing through the coils surrounding the electro-magnet *MM*, thereby producing **by induction** a correspondingly varying current in the line. This transmitter has, however, been superseded by the microphonic transmitter.

QUESTIONS ON CHAPTER X

1. A flat circular coil of copper wire is rotated in the Earth's field. Explain the production of an alternating current by this method, stating when this induced current is (*a*) a maximum, (*b*) a minimum. What considerations affect the value of the E.M.F. generated by the rotation of the coil?

2. Carefully explain the working of a simple direct current dynamo, clearly indicating the functions of (*a*) the Armature, (*b*) the Field Magnets, (*c*) the Commutator. Illustrate by carefully drawn diagrams.

3. Describe some form of dynamo armature designed so as to produce a steady E.M.F.

4. What factors limit the use of a direct current machine in generating power for industrial purposes? Give a very short description of the turbo-alternator.

5. Write descriptive notes on (*a*) the carbon filament lamp, (*b*) the gas filled Tungsten filament lamp, (*c*) the Pointolite lamp. Why are electric lamps usually arranged in parallel?

6. Describe the various ways in which an electric arc may be used as a source of (*a*) light, (*b*) heat, with special reference to (*a*) optical projection, (*b*) electric welding.

7. Give a description of some simple method of communicating electrically between two (*a*) near, (*b*) distant stations.

8. Carefully explain the use of the microphone and telephone in the transmission of speech by electricity along wires.

CHAPTER XI

THE CONSTITUTION OF MATTER—ELECTRONS—X-RAYS—RADIO-ACTIVITY—WIRELESS TELEGRAPHY AND TELEPHONY.

115. Discharge of Electricity through rarefied gases.

The large currents used in electrical industry impress us: their use in developing power by their passage through coils, motors and other appliances. Nevertheless, it is not by experimenting with large, but rather with relatively small currents, that the recent advance in electrical science has been achieved. The study of the electric spark, and of the nature of discharge through rarefied gas, has led to the discovery of the electron and has carried us a stage farther in understanding the constitution of matter.

The electric spark produced by an induction coil [see § 58] appears as a pulsating luminous streak, a lightning flash in miniature, and is accompanied by a loud crackling noise. But if the discharge takes place within a closed glass tube in which the pressure of the contained air is gradually reduced, its character undergoes several important changes.

Demonstration. Connect a closed glass tube, about 3 feet long, having two aluminium electrodes inserted through its ends

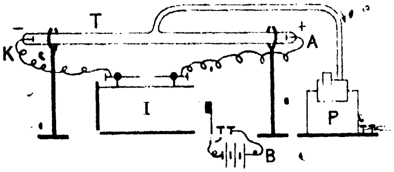

Fig. 173. *I*, Induction coil. *P*, Gaede air-pump. *B*, Battery. *T*, Tube from which air is pumped. *A*, Anode. *K*, Kathode.

(Fig. 173), to a *Gaede*[1] rotary air-pump, operated by an electric motor. The electrodes are connected "in parallel" to the secondary terminals of a powerful induction coil, across which a spark discharge is passed.

At first, the pressure in the tube is still atmospheric and no sparking occurs in the tube. But as the pressure of the contained air falls, the resistance drops until a long, brilliant purple discharge appears between the electrodes. Further reduction of pressure causes the luminosity to diminish, until a dark space (Faraday Dark Space) appears next to the Kathode (Fig. 174), and in the column are observed alternations of light and dark spaces called "striations." The Kathode itself appears luminous, and from its surface violet rays appear to shoot off. The walls of the tube glow with a greenish light.

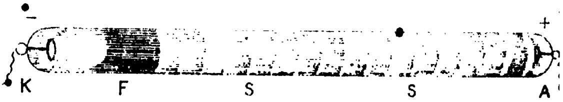

Fig. 174. *A*, Anode. *K*, Kathode. *F*, Faraday Dark Space. *S*, *S*, Striations.

If a strong magnet is brought near the tube (Fig. 175), so that a horizontal transverse magnetic field flows across it, the discharge is deflected upward or downward, cf. § 41.

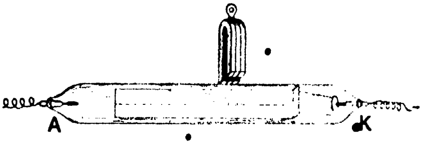

Fig. 175.

The various phenomena connected with these experiments were first thoroughly investigated by Sir Wm Crookes and later by a group of British scientists led by Sir J. J. Thomson, whose conclusions are of far reaching importance and are enumerated below:

---

[1] Excellent results are obtainable with this make of pump.

(i) The discharge consists of a stream of ultra-atomic corpuscles (*electrons*) projected in straight lines from the Kathode with high velocity.

(ii) These electrons are negatively charged.

(iii) The mass and charge of an electron are constant and independent of the nature of the electrodes and of the gas inside the tube.

The term "Kathode Rays" was given to this stream of electrons. These conclusions may be illustrated by the following experiments:

(i) A stream of Kathode Rays is passed through a vacuum tube in which is inserted a metallic obstacle (*e.g.* Maltese Cross). A sharp shadow is thrown upon the walls of the tube (Fig. 176).

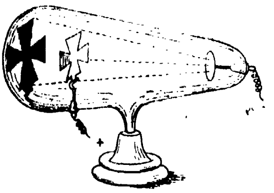

Fig. 176.

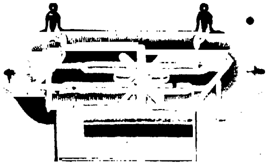

Fig. 177.

(ii) Again in a vacuous tube a light paddle wheel of mica is placed, so that the rays fall on the upper portion of the wheel: it rotates as if struck by a propelling stream of particles. A powerful magnet will deflect the rays downwards so that the wheel rotates back towards its original position (Fig. 177).

116. The charge on an electron and its mass.

The ratio of the charge on an electron (e) and its mass (m) was obtained by Sir J. J. Thomson by observing the deflection produced on a stream of electrons by uniform magnetic and electric fields. He also found the ratio e/m by measuring the rate of fall of a cloud of particles of moisture condensed on electrons. The relation of the charge to the mass was in each case the same.

From these and many other confirming experiments it was found that

(*a*) The electron is a constituent of all matter.

(*b*) The mass of an electron is $\frac{1}{1850}$ the mass of an atom of hydrogen.

(*c*) The charge on an electron is equal to the charge on an atom of hydrogen in electrolysis, viz. $4{\cdot}77 \times 10^{-10}$ electrostatic C.G.S. units.

Positive Rays.

Positively charged particles have also been discovered in the discharge tube proceeding in a direction opposite to the Kathode stream. *But their mass has always been found to be of atomic dimensions.* It is therefore likely that these positively charged particles are the nuclei of atoms from which electrons have become separated. Consequently, it is assumed that practically the whole mass of the atom is carried by the *nucleus*, which has a charge of *positive* electricity just sufficient to neutralize the charge on its few extremely light satellites, the electrons.

117. X-Rays. (Röntgen Rays.)

The *waves* which constitute X-Rays are produced by the impact of a stream of electrons on a solid object.

An X-Ray tube (Fig. 178) consists of an almost vacuous glass bulb in which a stream of Kathode Rays, proceeding from a *concave* negative electrode, is concentrated on one spot of a platinum platform T (*anti-Kathode*).

Demonstration.

Paint the outside of an X-Ray bulb with lamp black in order to get rid of the phosphorescence caused by the Kathode Rays. *Darken* the room and on passing a discharge from a powerful induction coil through the tube, nothing is observed by the eye. If, however, a *screen* coated with *barium platino-cyanide* is placed near the bulb, this chemical substance glows with a bluish phosphorescence. Thus the X-Rays, themselves *invisible*, may be detected by their effect on certain chemical substances.

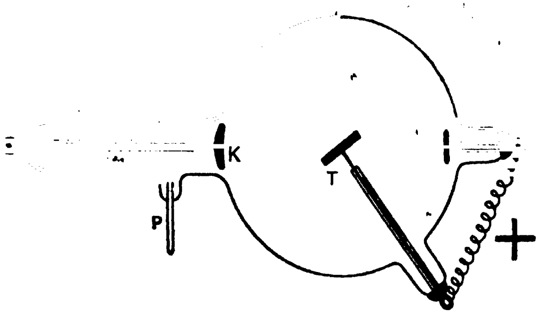

Fig. 178. Röntgen-Ray Bulb.

If the hand is placed on the side of the screen nearest the bulb, the X-Rays, penetrating the flesh but not the bone, cast a shadow of the carpal and metacarpal bones which is clearly seen.

Exp. (i). Repeat, substituting for the screen a photographic plate wrapped in black paper. Develop after exposure for 30 seconds (say).

Exp. (ii). Deflect the stream of electrons from the anti-kathode by means of a powerful electro-magnet: the X-Ray effect disappears.

Properties of X-Rays.

X-Rays have the following properties:

(*a*) Invisible to the human eye, they consist of waves or pulses whose wave-length is shorter than that of light. These pulses are produced by the impact of electrons.

(*b*) The rays have great penetrating power, passing through many substances opaque to ordinary light, *e.g.* wood, flesh, cloth, but are stopped by optically denser substances, *e.g.* bone and metal.

(*c*) They may be detected by their effect on certain chemical substances, *e.g.* silver salts (photographic plates), barium platino-cyanide, etc.

(*d*) They render the gas through which they pass a conductor of electricity by liberating electrons from the atoms (ionization).

118. Radio-activity.

It has been suggested in § 10 that the atomic system may be not unlike a planetary system in which the electrons move around the central positive nucleus. In certain substances of high atomic weight such as uranium (A.W. 238) and **radium** (A.W. 226), the atomic system is supposed to be unstable and frequent miniature internal explosions occur, electrons and portions of the nucleus being thrown out of the atom with great velocity. Three types of radiation are emitted from radio-active substances, viz.:

α rays: Positively charged particles (helium) whose velocity of projection is $\frac{1}{12}$ velocity of light.

β rays: Electrons travelling with an average speed of half the velocity of light.

γ rays: Identical with X-Rays and caused by the sudden projection and big initial acceleration of the electrons in the *β* rays.

119. The Transmutation of Elements.

It will readily be seen from the new theory of the atom [§ 10] that after the expulsion of the *α* and *β* particles, the atomic system must necessarily be regrouped, and a new atom formed possessing properties different from those originally observed, *i.e. a new element is produced.* This has been proved by Rutherford's work on the transmutation of elements, by which he has shown that Uranium is the parent of a long chain of elements in which are included Radium, Polonium, and Lead.

WIRELESS TELEGRAPHY.

Just this—the tiniest flash of energy
Started beyond the furthest reach of space
Makes ripples that will spread until the rings
Circling in the black pool of time will touch
All other forms of energy and light.
From *The Ohm's Book*, EDGAR LEE MASTERS.

120. Demonstration. An electrically driven tuning fork (Fig. 179) has a bent metal tongue or "dipper" (*P*), attached to one of its prongs, which dips into a trough of water or mercury. Turn on the current and the fork is set into rapid vibration, producing by the up and down motion of the dipper, ever increasing wave rings in the liquid. Specks of lycopodium floating quietly on the surface some distance away from the centre of the disturbance are agitated by the wave motion, moving *not* laterally but vertically, whilst the wave passes on in an ever widening circle.

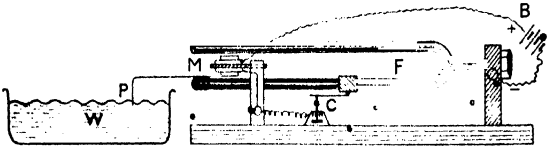

Fig. 179. *B*, Battery. *F*, Large Tuning fork. *C*, Contact breaker. *W*, Water. *P*, Vibrating point. *M*, Electro-magnet.

These waves have a definite *velocity* (vel. of wave motion $= V$) and a definite wave-length (λ), whilst a definite number (n) pass a lycopodium speck in a given interval of time. It follows that $V = n\lambda$.

This experiment, which may be "projected" on a screen very successfully by means of an optical lantern, illustrates the chief facts of wave motion. In this chapter we shall deal with *electric* waves produced in the *ether of space* [§ 4] by a vibrating, or as it is termed, an *oscillatory* electric current.

121. Resonance or Tuning.

Exp. (i) *A* and *B* are two simple pendulums suspended from a horizontal flexible lath clamped to an upright stand (Fig. 180). It is found, when the strings are *unequal* in length, that if one pendulum is set into vibration the other still remains at rest: if, however, the lengths of the strings are made exactly equal, the motion of the moving pendulum is communicated to its neighbour and both vibrate together.

Exp. (ii) Obtain two tuning forks of *equal* pitch, mounted on resonance boxes. Strike one fork and hold it a short distance from the other. Next silence the vibrating fork with the fingers: the note of the second fork is then distinctly heard.

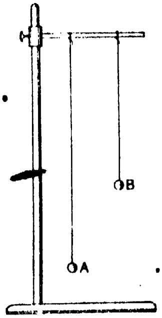

Fig. 180.

This phenomenon known as *Resonance* or *Tuning* illustrates a fact of great importance in the study of Wireless Telegraphy: that any wave motion is communicated to, or detected by a suitable instrument having the same frequency as the vibrating instrument producing the motion; *i.e.* when the producer and receiver give out or respond to waves of the same wave-lengths.

122. Condenser Discharge—Oscillatory Circuit.

In Fig. 181 *a* is illustrated a method of obtaining a brilliant spark discharge using a Leyden jar as condenser. One of the terminals of an induction coil is connected to the knob of a Leyden jar. The second terminal is joined to the outer coating of the jar by a wire which is continued by a piece of stout copper wire attached to a second knob thus forming the spark-gap *S'*. On passing a current through the coil a succession of sparks cross the gap *S'*.

It was shown by Kelvin in 1853, that when a condenser is discharged in this manner, the electricity does not simply rush across the spark-gap in one direction, but surges *backwards* and *forwards*, charging and discharging the condenser in successive cycles until its energy is frittered away and damped by the resistance of the circuit.

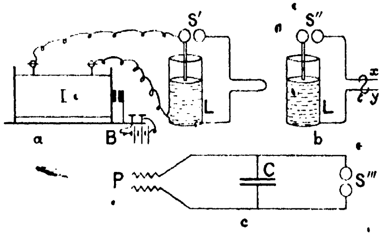

Fig. 181. *I*, Induction coil. *L*, Leyden Jar Condenser. *S*, Spark-Gap. *C*, Condenser. *P*, Connection to influence machine or coil.

An electrical circuit, such as this, containing a condenser (Fig. 181 *c*) is known as an *oscillatory circuit*, owing to the fact that an oscillating current of high frequency traverses the circuit *C*, *A*, *S*‴, *B*, whenever a spark crosses the gap *S*‴. This rapidly alternating current constitutes an electrically vibrating source, and, as Clerk Maxwell predicted in 1863, produces waves in the ether which travel out with the velocity of light.

123. Electrical Resonance or Tuning.

These electric waves may be detected in a very simple manner by means of an experiment devised by Sir Oliver Lodge (Fig. 181 *b*). A similar circuit consisting of a Leyden jar, spark-gap *S*″, and parallel wires *x*, *y*, connected by a sliding contact *t*, is placed a short distance away from the transmitting apparatus (Fig. 181 *a*). Whenever the key is pressed in the primary circuit, a spark will pass across the gap *S*″ at the same time as it passes across *S*′, provided that *S*″ is not more than $\frac{1}{16}$″ in width and that the second circuit is placed *in tune* with the first by adjusting the position of the sliding contact (*t*).

124. The work of Marconi.

In his first experiments Marconi substituted "aerials" or "antennae" Fig. 184 for the condenser *C* (Fig. 181 *c*). To one knob of the spark-gap was fastened a long wire (aerial) suspended in the air between two insulated masts. The other knob was "earthed" by connecting it to a metal plate *E* sunk in the ground. Similar wires connected the terminals of the detector used in the receiving apparatus. This system may be regarded as a condenser, the aerial and the earth constituting the plates with the air as the dielectric between them. On charging and discharging the aerial by means of the coil, the electricity surges backwards and forwards across the spark-gap and by its oscillation produces waves in the ether which travel out with the velocity of light.

For types of aerials, see Fig. 184.

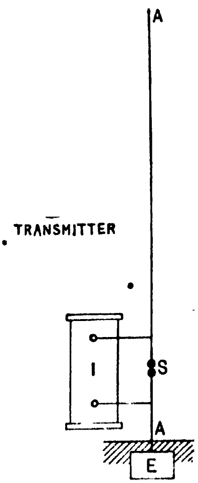

Fig. 182. Earthed wire, Spark-Gap and Aerial.

Coupled Oscillatory Circuits.

The "open" oscillatory circuit has many disadvantages, the chief being, (*a*) leakage of energy in brush discharges due to the high voltage required to produce the requisite power, and (*b*) breakdown of insulation of the aerial in wet weather. It was therefore advantageous to return to the closed oscillatory circuit Fig. 183 and operate by induction on the aerial. This is known as a coupled circuit.

125. The Transmitter.

Fig. 183 explains itself. A coil of wire *L* containing a large number of turns is introduced into the closed oscillatory circuit of § 122, so as to act by mutual induction on a coil *N* which connects the aerial and the earth plate. By altering the capacity of the condenser *C* and the number of turns in the coil *L* we can

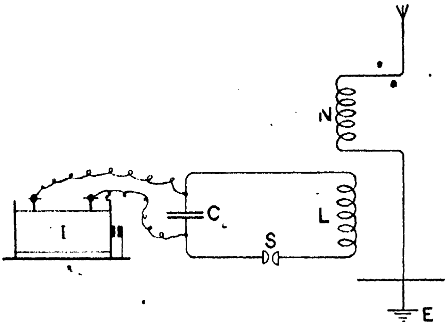

Fig. 183. Coupled oscillatory circuit.

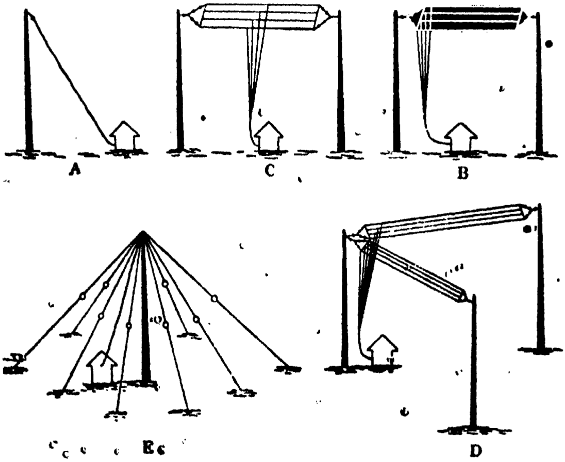

Fig. 184. Various Antennae or Aerials.

bring this circuit "in tune" with the aerial, so that, when a series of sparks passes across S, and produces an oscillating current in the circuit CLS, a similar current is induced in the aerial which in its turn sends out a train of electric waves. The connections of the corresponding receiving circuit are based on the same principle, the wave-length of the receiving circuit being "tuned" to that of the sending station.

126. The Crystal Detector.

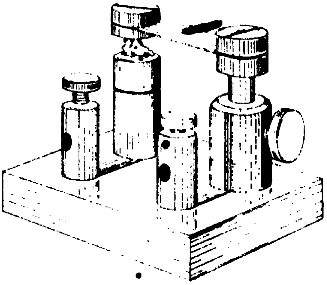

Fig. 185.

One of the simplest and most efficient methods for the detection and reception of electric waves is in the use of certain crystals such as carborundum, zincite-chalcopyrite ("Perikon"), zincite-tellurium. It is found that if a suitable crystal is held between two metal supports (Fig. 185) it conducts electricity much better in one direction than the other. Consequently, if the crystal is placed in a closed oscillatory circuit, the current in one direction will be damped down whilst the current in the other direction will pass through unimpeded. Thus the crystal acts as a rectifier converting the alternating current into a current flowing in one direction.

In order to convert the electric waves into sound waves for the purposes of receiving, a high resistance telephone is also introduced into the crystal circuit. When a train of waves reaches the receiver it is transformed by the crystal into a "one way" current whose effect is to exert a pull on the diaphragm of the telephone producing a sharp click. If the key at the transmitting station is depressed for a short time we get a series of sparks of definite frequency. Each spark produces its own group of waves which in its turn causes a click in the telephone. A succession of clicks is therefore heard as a buzzing note for as long a time as the key in the sending station is pressed. By depressing the key for long or short intervals, communication in the Morse Code is made possible.

127. The Receiving Station.

As in transmission, so in reception it was found that the best results were obtained when the aerial was used to operate by induction on the receiving circuit. A plan of a receiving circuit is shown in Fig. 186, in which a crystal *K* is used as the detector. In practice, the crystal works far more efficiently if a steady potential difference is maintained between its ends. This is applied by means of a battery and potentiometer (not shown in figure). It is important that the receiving circuit and the aerial circuit should be both in tune with one another and with the transmitting station. This is accomplished by varying the capacity of the condenser and the number of turns in the coils.

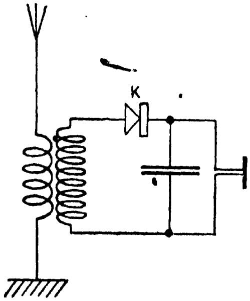

Fig. 186. Receiving Station with crystal detector.

128. The Thermionic Valve and its use in connection with Wireless Telegraphy and Telephony.

A notable advance in the science of Wireless Telegraphy was made in 1904 by a discovery of Fleming and his invention of the Thermionic Valve. The valve consists of a vacuum glow lamp containing a Tungsten filament *F* (Fig.

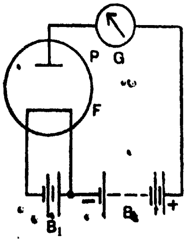

Fig. 187. Fleming Valve.

187) and a metal plate P. The filament F is heated to incandescence by means of an auxiliary battery B_1. A filament in this condition emits (– ve) electrons, but ordinarily these electrons remain in the neighbourhood of the filament. If however a potential difference is applied between the plate and the filament by the battery B_2 so that the plate has a positive potential with respect to the filament, a stream of electrons is drawn across the intervening space and may be recorded by the galvanometer G. On the other hand, if the plate P is of negative potential with respect to the filament, the electrons are repelled and no current passes. If the plate P is connected either directly, or, by induction, to an aerial (Fig. 188), the potential of P will alternately be positive or negative, and therefore, during one half of each complete oscillation a current will pass between F and P. This instrument can therefore be likened to a valve, for a current can pass through it in one direction only. If a telephone (Fig. 188) is included in the circuit, it will emit a musical note whenever signals, caused by waves in the ether of suitable wave-length, reach the receiving station.

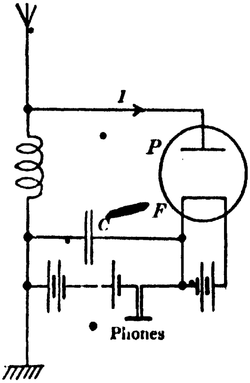

Fig. 188. Receiving Station with Fleming Valve.

129. The Triode Valve or Amplifier.

The efficiency of the Fleming Valve was greatly improved, in 1913, by De Forest who inserted a grid G, consisting of a wire mesh or spiral, between the filament F and the plate A. A steady E.M.F. is applied across the space between the plate A and the filament F by a battery of dry cells (about 50 volts)[1] so that A is charged to a positive potential with respect to the filament. If the filament is heated to incandescence, this positive charge draws a steady stream of electrons from the hot filament into the plate telephone circuit. (Fig. 189.)

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[1] The E.M.F. required varies with the particular form of valve in use.

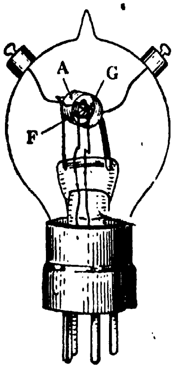


Fig. 189. Triode Valve, French Pattern.

Suppose however that the grid G is subjected to a varying potential. Whenever G has a negative charge the electrons are driven back, and no electrons reach the plate through the meshes of the grid. On the other hand if G has a positive potential, the electron flow is assisted by the presence of the grid, and a large current will pass across to A and enter the telephone circuit. Very small changes of potential on the grid cause great current differences in the telephones, these currents being derived from the battery which heats the filament.

In practice the grid is connected to the aerials (Fig. 190), and any signals which reach the valve create small, rapid variations of potential in the grid, which in their

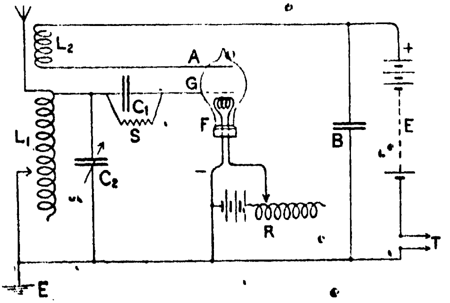


Fig. 190. Receiver for Wireless Telegraphy or Telephony with Triode
***T*, connection to phones or amplifier.**

turn, produce greatly amplified direct currents in the plate filament circuit, in which the telephone is placed.

130. Tuning Coil.

In Fig. 191 is depicted a tuning apparatus which has been found extremely useful for reception in both Wireless Telegraphy and Telephony. The coil L_1, diameter 3·2″, contains 135 turns of copper wire, No. 28 single layer. The reaction coil L_2 contains 52 turns of No. 28 wire wound on a cylinder 2·75″ diameter which moves inside the coil L_1. Tuning is effected (*a*) by introducing new turns ("tappings") into the coil L_1 by switching over the dial contact *P*; (*b*) by moving the coil L_2 to and fro within the outer coil by means of the rod *R*.

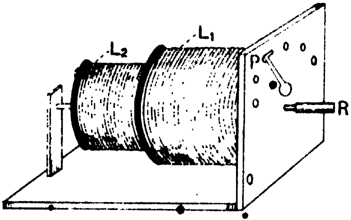


Fig. 191. Tuning Coil.

The Receiving Station (Fig. 190).

Thirteen or fourteen four-volt flash lamp batteries provide the E.M.F. across the filament-plate gap, a four-volt accumulator being used to heat the filament. C_1 and C_2 are variable condensers of maximum capacities ·005 and ·001 microfarad respectively: *B* is a small blocking condenser across the phones, *S* a "grid leak" of 2 megohms resistance. A Cossar valve may be used. The apparatus is capable of receiving waves from 200–1800 metres (λ).

131. Wireless Telephony.

The waves produced by the passage of a spark across a gap are "damped" waves, *i.e.* waves whose amplitude steadily diminishes and whose energy quickly dies away. These waves are useless for the transmission of speech, and for this purpose undamped or continuous waves are employed. One of the greatest advantages of the triode valve is that under certain conditions it can be made to emit continuous waves, *i.e.* waves of constant amplitude.

Fig. 192 represents a simple and efficient transmitting set for a wireless telephone. On careful examination of the connections it will be seen that it consists of *two closed oscillatory* circuits, viz. the plate circuit P, L, C_1, F (containing the aerial, earth and condenser C_1) and the grid circuit A, C_2, G, F (containing the grid condenser C_2). Let us suppose that an electric oscillation reaches the aerial: this will create an alternating potential in the grid and hence an oscillatory current in the grid circuit. The variations in the potential of the grid will correspondingly affect the strength of the current that is driven across the space FP and therefore will produce an oscillatory current in the plate circuit. If the grid and plate circuits are properly tuned, these alternating currents, by reacting on and reinforcing one another, will maintain their flow and cause a continuous oscillating current to be developed, which

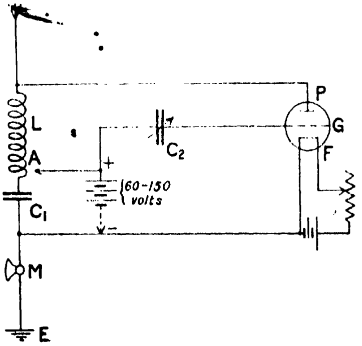


Fig. 192.

on passing through the coil L gives rise to a train of continuous waves projected into space from the aerial.

When the valve is oscillating continuous waves of constant amplitude are sent out from the aerial. But if a microphone is inserted in the system at M the resistance of the aerial circuit is altered by speaking into the microphone [see § 114], and the strength of the alternating current in the aerials is altered correspondingly, as the diaphragm vibrates under the influence of the sound waves. The amplitude of the waves emitted is therefore affected, and these waves, in turn, on reaching the receiving aerials cause corresponding changes in the potential of the grid which affect the thermionic current. These changes in the current across the vacuous space in the valve, by being passed through a series of valve amplifiers are magnified further, to such an extent, that the human voice can be reproduced with great accuracy in the telephones.

QUESTIONS ON CHAPTER XI

1. Contrast the appearance and character of an electric spark in air (*a*) at atmospheric pressure, (*b*) at very low pressures in a discharge tube.

2. What is an electron? Describe the experiments which led to its discovery and to the indication of its properties.

3. What do these experiments teach us of the nature of the atom and the constitution of matter?

4. Describe the production and properties of X-Rays and show how they differ from Kathode Rays. How would you prepare a radiograph of a foreign body in the forearm?

5. What do you understand by Radio-activity? What are the chief radio-active substances and what evidence is there for the assumption that they are constantly changing their nature?

6. What are the characteristics of a condenser discharge and how is such a discharge made use of in the production of electric waves?

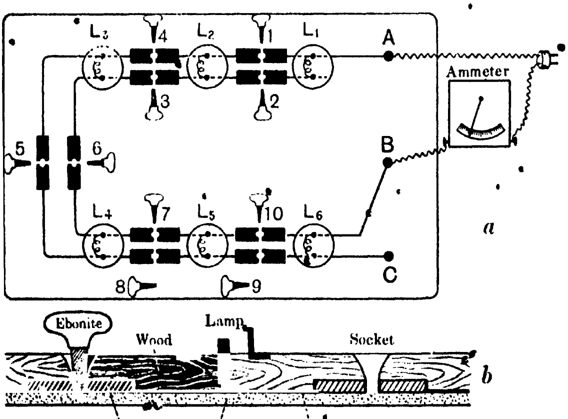
7. Give a short account of either (*a*) a crystal detector, (*b*) a thermionic valve for use in the reception of wireless signals.

8. For what purpose are the following required in a Transmitting set: (*a*) aerials, (*b*) spark-gap, (*c*) condenser, (*d*) induction coil?

APPENDIX I

Lamp Resistance Board.

A suitable resistance board, giving resistances varying from 80–3000 ohms and suitable for use with the lamp mains, is shown in Fig. 193 *a*. The apparatus may be put together in the school workshop. Two main wires with terminals at *A* and *B* respectvely pass round the underside of a board, shown in the plan, nd are imbedded in grooves filled with paraffin wax. Six lamp-olders are fixed at $L_1 \ldots L_6$ so that when a lamp is inserted the



Figs. 193 *a* and *b*.

two wires are bridged by the lamp filament at these points. The wires are interrupted at the five intervals between the lamps, but each may be made continuous by the insertion of plugs at the numbered junctions.

Demonstration on method of using. (*a*) **Lamps in parallel** (resistance decreased).

Terminals *A* and *B* *only* are used and joined to the main supply with an ammeter (reading to 3 amps.) in the circuit. Insert all the plugs: no current will flow until the two wires are joined by inserting lamps in the lamp-holders.

The circuit was of 220 volts and the lamps used were Ediswan Carbon filament 32 c.p. of approx. 490 ohms resistance. One, two...to six lamps were inserted in parallel and the corresponding ammeter readings taken.

Lamps inserted	Ampères	P. D. Volts between *A* and *B*	$\frac{E}{C} = R$ ohms
1	0·45	220 Volts	488
2	0·90		245
3	1·35		163
4	1·82		122
5	2·30		95
6	2·75		80

Draw the curve $\frac{\text{Lamps in Parallel}}{\text{Resistance}}$.

(*b*) **Lamps in series** (resistance increased). *A* is always joined to one of the main terminals. **Caution:** the other main terminal must *never be joined to C or B without first removing a plug* (usually No. 1) *from the outer wire:* this prevents short-circuiting. Insert all the lamps and plugs **except No. 1.** Join *B* to the ammeter, **then** switch on the main current, which now passes through L_1. Next remove plug No. 3 and join *C* to the ammeter. The current now passes through L_1 and L_2 *in series.*

Notice that the lamps fade or emit no light, and the ammeter reading falls. Remove plug No. 5, and finally No. 7 and No. 9, changing the ammeter wire from B to C alternately, and take current readings (ampères):

Lamps in Series	Current Amps.	P. D. Volts	$\frac{E}{C}=R$ Ohms Approx.
1	0·450	220	490
2	0·225		980
3	0·150		1470
4	0·112		1960
5	0·090		2450
6	0·075		2940

Draw a curve $\begin{matrix}\text{Lamps in Series}\\ \text{Resistance}\end{matrix}$.

(*c*) **Lamps in parallel and in series.**

Vary the above by placing some lamps in series, others in parallel, and calculate the resistance.

Repeated Caution, if the *main supply* is used:

(1) *Always remove plug No.* 1 *when using terminals A and C.*

(2) *Always have benches, fittings and fingers absolutely dry.*

(3) *Make certain that the connections are correct before switching on the main current.*

N.B. The chief difference between using the main supply and a battery of cells is that the P. D. between the terminals remains constant ($=E$) in the former case, whereas, when a battery is used, the P. D. falls when current has passed for a shorter or a longer time according to R; then P. D. $<E$ (see § 66).

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